

Contents

Foreword

vi

Preface

vii

How to cite this work viii

A note on conventions viii

Authors ix

A The facilities

1

1 The *B* Factories 1

1.1 Introduction 1

1.1.1 Testing the KM idea 1

1.1.2 Three miracles 1

1.2 The path to the *B* Factories 21.2.1 Requirements for a *B* Factory 2

1.2.2 Early proposals 3

1.2.3 Asymmetric colliders 3

1.2.4 A different approach 4

1.3 PEP-II and KEKB 5

1.4 Detectors for the *B* Factories 61.4.1 The *BABAR* detector collaboration 7

1.4.2 Formation of the Belle collaboration 9

1.4.3 Building the *BABAR* detector 10

1.4.4 Building the Belle detector 14

1.5 Physics at last 16

1.5.1 Establishing *CP* violation in *B* meson decay 171.5.2 The premature end of *BABAR* data taking 17

1.5.3 The final Belle data taking runs 17

2 The collaborations and detectors 18

2.1 Introduction 18

2.1.1 The *BABAR* and Belle collaborations 202.1.2 The *BABAR* detector 21

2.1.3 The Belle detector 21

2.2 *BABAR* and Belle comparative descriptions 23

2.2.1 Silicon detector 23

2.2.2 Drift chamber 26

2.2.3 Charged particle identification 28

2.2.4 Electromagnetic calorimeter 30

2.2.5 Muon detector 32

2.2.6 Trigger 34

2.2.7 Online and DAQ 35

2.2.8 Background and mitigation 36

2.2.9 Conclusion: main common points, main differences 38

3 Data processing and Monte Carlo production 40

3.1 Introduction: general organization of the data taking, data reconstruction and MC production 40

3.2 Data taking 41

3.2.1 Integrated luminosity vs. time; luminosity counting 42

3.2.2 Major hardware/online upgrades which modified the quality of *BABAR* data 43

3.2.3 Major hardware/online upgrades which modified the quality of Belle data 44

3.3 Data Reconstruction 46

3.3.1 Introduction 46

3.3.2 The *BABAR* prompt reconstruction 46

3.3.3 The Belle data reconstruction 46

3.4 Monte Carlo simulation production 47

3.4.1 Introduction 47

3.4.2 Event generators 48

3.4.3 Detector Simulation 48

3.4.4 MC production systems 49

3.4.5 Differences between *BABAR* and Belle simulations 49

3.5 Event skimming 51

3.5.1 Introduction: purpose of event skimming 51

3.5.2 Skimming in *BABAR* 51

3.5.3 Skimming in Belle 52

3.6 Data quality and *B* counting 53

3.6.1 The control of data quality 53

3.6.2 *B*-counting techniques 55

3.7 Long Term Data Access system 57

3.7.1 The *BABAR* approach 57

3.7.2 The Belle approach 58

B Tools and methods

59

4 Multivariate methods and analysis optimization 59

4.1 Introduction 59

4.2 Notation 59

4.3 Figures of merit 59

4.4 Methods 60

4.4.1 Rectangular cuts 61

4.4.2 Likelihood method 61

4.4.3 Linear discriminants 62

4.4.4 Neural nets 62

4.4.5 Binary decision trees 63

4.4.6 Boosting 63

4.4.7 Bagging and random forest 64

4.4.8 Error correcting output code 64

4.5 Available tools 65

5 Charged particle identification 67

5.1 Introduction 67

5.1.1 Definitions 67

5.1.2 Subdetectors providing PID information 67

5.2 PID algorithms and multivariate methods 67

5.2.1 Belle algorithms 68

5.2.2 *BABAR* algorithms 685.3 *BABAR* PID performance and systematics 695.3.1 History of PID performance in *BABAR* 69

5.3.2 Systematic effects 69

5.4 Belle PID performance and systematics 70

6 Vertexing 73

6.1 The role of vertexing in the *B* Factories 73

6.2 Track parameterization and resolution 73

6.3 Vertex fitting by χ^2 minimization 75

6.4 Primary vertex reconstruction and beamspot calibration 77

6.5 Δt determination 796.5.1 Reconstruction of the B_{tag} vertex 796.5.2 From vertex positions to Δt 806.5.3 Δt resolution function 817 *B*-meson reconstruction 837.1 Full hadronic *B*-meson reconstruction 837.1.1 Kinematical discrimination of *B* mesons 84

7.2	Semileptonic B -meson reconstruction	87	11.2.1	Extended ML formalism	132
7.3	Partial B -meson reconstruction	88	11.2.2	Extending a model to multiple dimensions	132
7.3.1	$B \rightarrow D^{*\pm} X$ decays	88	11.2.3	s Plots	133
7.3.2	$B \rightarrow D^{*\pm} \ell \nu_\ell$ decays	90	11.3	Structure of models for decay time-dependent measurements	134
7.4	Recoil B -meson reconstruction	90	11.3.1	Visualization of $p.d.f.s$ of decay time distributions	135
7.4.1	Hadronic tag B reconstruction	92	11.4	Techniques used for constraining nuisance parameters from control samples	136
7.4.2	Semileptonic tag B reconstruction	95	11.4.1	Simultaneous fits to control regions	136
7.4.3	Inclusive B_{tag} reconstruction	96	11.4.2	Simultaneous fits to multiple signal regions	136
7.4.4	Double tagging	97	11.5	Miscellaneous issues	137
7.5	Summary	99	11.5.1	Background subtraction and weighted events	137
8	B -flavor tagging	100	11.5.2	Validation of ML fits on complex models	138
8.1	Introduction	100	11.5.3	Computational optimizations of likelihood calculations	139
8.2	Definitions	100	12	Angular analysis	140
8.3	Tagging categories	101	12.1	Formalism	140
8.4	Dilution factor and effective tagging efficiency	101	12.1.1	Spin and helicity	140
8.5	Physics sources of flavor information	102	12.1.2	Angular bases	140
8.5.1	Leptons	102	12.1.3	Angular distributions in the helicity basis	141
8.5.2	Kaons	102	12.1.4	Angular distributions in the transversity basis	141
8.5.3	Slow pions	102	12.1.5	CP violation	142
8.5.4	Correlation of kaons and slow pions	103	12.1.6	Time dependence	142
8.5.5	High-momentum particles	103	12.2	List of modes	143
8.5.6	Correlation of fast and slow particles	103	12.2.1	$V \rightarrow PP$	143
8.5.7	Λ baryons	103	12.2.2	$P \rightarrow VP, V \rightarrow PP$	143
8.6	Specific flavor tagging algorithms	104	12.2.3	$P \rightarrow V\gamma, V \rightarrow PP$ and $P \rightarrow T\gamma, T \rightarrow PP$	144
8.6.1	Multivariate tagging methods	104	12.2.4	$P \rightarrow VV, V \rightarrow PP$	144
8.6.2	Systematic effects	104	12.2.5	$P \rightarrow VV, V_1 \rightarrow P\gamma, V_2 \rightarrow PP$	144
8.6.3	Flavor tagging in $BABAR$	104	12.2.6	$P \rightarrow VV, V \rightarrow P\gamma$	145
8.6.4	Flavor tagging in Belle	106	12.2.7	$P \rightarrow VV, V_1 \rightarrow PP, V_2 \rightarrow ll$	145
9	Background suppression for B decays	109	12.2.8	$P \rightarrow VV, V_1 \rightarrow PP, V_2 \rightarrow V\gamma$	145
9.1	Introduction	109	12.2.9	$P \rightarrow TV, T \rightarrow PP, V \rightarrow PP$	146
9.2	Main backgrounds to B decays	109	12.3	Analysis details	146
9.3	Topological discrimination	109	12.3.1	Generators	146
9.4	$BABAR$ strategy	110	12.3.2	Experimental effects	146
9.4.1	Linear discriminants	111	12.3.3	Caveats	146
9.4.2	Nonlinear discriminants	112	12.4	Angular fits	147
9.4.3	Including additional sources of background suppression	113	12.4.1	Dedicated or global fits	147
9.5	Belle strategy	114	12.4.2	Partial and complete angular analyses	147
9.5.1	SFW	114	12.4.3	Other angular analyses	148
9.5.2	KSF	114	13	Dalitz-plot analysis	149
9.5.3	Additional variables and neural network	115	13.1	Introduction	149
9.6	Summary	117	13.1.1	Three-body decay phase space	149
10	Mixing and time-dependent analyses	119	13.1.2	Boundaries, kinematic constraints	149
10.1	Neutral meson mixing	119	13.2	Amplitude description	150
10.2	Time-dependent evolution	122	13.2.1	Isobar formalism	150
10.3	Use of flavor tagging	123	13.2.2	K-matrix formalism	151
10.4	Resolution of Δt	124	13.2.3	Nonresonant description	153
10.5	Modeling the Δt distribution for background events	126	13.2.4	Time-dependent analyses	153
10.6	Parameter extraction from data	126	13.3	Experimental effects	154
11	Maximum likelihood fitting	128	13.3.1	Backgrounds	154
11.1	Formalism of maximum likelihood fits	128	13.3.2	Efficiency	154
11.1.1	Probability Density Functions	128	13.3.3	Misreconstructed signal	155
11.1.2	Maximum Likelihood estimation of model parameters	128	13.4	Technical details	155
11.1.3	Estimating the statistical uncertainty using the likelihood	129	13.4.1	Square Dalitz plot	155
11.1.4	Hypothesis testing and significance	130	13.4.2	Complex coefficients	156
11.1.5	Computational aspects of maximum likelihood estimates	130			
11.2	Structure of models for signal yield measurements and rare decay searches	131			

13.4.3	Fitting	157	17.4	Charmless B decays	236
13.4.4	Fit fractions	158	17.4.1	Introduction	236
13.5	Model uncertainties	158	17.4.2	Theoretical overview	237
13.5.1	Estimation of model uncertainties	158	17.4.3	Experimental techniques	241
13.5.2	Model-independent analysis	159	17.4.4	Two-body decays	245
13.5.3	Model independent partial wave analysis	159	17.4.5	Quasi-two-body decays	248
14	Blind analysis	160	17.4.6	Dalitz experimental techniques	263
14.1	Definition and brief history	160	17.4.7	Three-body and Dalitz decays	268
14.2	Setting upper limits: a quantitative example	160	17.4.8	Summary	272
14.3	Precision measurements	161	17.5	B -meson lifetimes, $B^0 - \bar{B}^0$ mixing, and sym-	
14.4	Examples from Belle	161		metry violation searches	274
14.5	Examples from BABAR	162	17.5.1	B -meson lifetimes	274
15	Systematic error estimation	164	17.5.2	$B^0 - \bar{B}^0$ mixing	280
15.1	Differences between data and simulation	164	17.5.3	Tests of quantum entanglement	289
15.1.1	Track reconstruction	164	17.5.4	Violation of CP , T , and CPT symme-	
15.1.2	K_S^0 and Λ reconstruction	167		tries in $B^0 - \bar{B}^0$ mixing	292
15.1.3	Particle identification	168	17.5.5	Lorentz invariance violation in $B^0 - \bar{B}^0$	
15.1.4	π^0 reconstruction	168		mixing	298
15.1.5	High-energy photons	170	17.6	ϕ_1 , or β	302
15.2	Analysis procedure	170	17.6.1	Overview of ϕ_1 measurement at the B	
15.2.1	External input	171		Factories	302
15.2.2	Modeling of background	171	17.6.2	Transitions and formalism	304
15.2.3	Fit bias	171	17.6.3	ϕ_1 from $b \rightarrow c\bar{c}s$ decays	305
15.3	Systematic effects for time-dependent analyses	172	17.6.4	ϕ_1 from $b \rightarrow c\bar{c}d$ decays	308
15.3.1	Alignment of the vertex detector	172	17.6.5	ϕ_1 from $b \rightarrow c\bar{u}d$ decays	311
15.3.2	Beamspot position, z scale and boost	172	17.6.6	ϕ_1 from charmless quasi-two-body B	
15.3.3	Resolution function and flavor tagging			decays	312
	parameters	173	17.6.7	ϕ_1 from charmless three-body decays	314
15.3.4	The effect of physics parameters	173	17.6.8	Resolving discrete ambiguities in ϕ_1	317
15.3.5	CP violation in background components	173	17.6.9	Time-reversal violation in $b \rightarrow c\bar{c}s$ decays	322
15.3.6	Tag-side interference	174	17.6.10	ϕ_1 summary	326
15.4	Summary	175	17.7	ϕ_2 , or α	328
			17.7.1	Introduction	329
			17.7.2	Event reconstruction	333
			17.7.3	$B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$	333
			17.7.4	$B^0 \rightarrow (\rho\pi)^0$	338
			17.7.5	$B^0 \rightarrow a_1^\pm(1260)\pi^\mp$	339
			17.7.6	$SU(3)$ constraint using $B^0 \rightarrow \rho^+\rho^-$,	
				and $B^+ \rightarrow K^{*0}\rho^+$	341
			17.7.7	Summary	342
			17.8	ϕ_3 , or γ	345
			17.8.1	Introduction	345
			17.8.2	GLW method	345
			17.8.3	ADS method	347
			17.8.4	Dalitz plot (GGSZ) method	350
			17.8.5	$\sin(2\phi_1 + \phi_3)$	360
			17.8.6	Determination of ϕ_3 and discussion	363
			17.9	Radiative and electroweak penguin decays	365
			17.9.1	Theoretical framework	365
			17.9.2	Inclusive $b \rightarrow s\gamma$	370
			17.9.3	Exclusive $b \rightarrow s\gamma$	377
			17.9.4	Exclusive and inclusive $b \rightarrow s(d)\gamma$	379
			17.9.5	Rate asymmetries in $b \rightarrow s(d)\gamma$	382
			17.9.6	Time-dependent CP asymmetries	385
			17.9.7	Electroweak penguin decays $b \rightarrow s(d)\ell^+\ell^-$	387
			17.9.8	Electroweak penguin decays $b \rightarrow s(d)\nu\bar{\nu}$	393
			17.10	$B^+ \rightarrow \ell^+\nu(\gamma)$ and $B \rightarrow D^{(*)}\tau\nu$	395
			17.10.1	Overview	395
			17.10.2	$B^+ \rightarrow \ell^+\nu(\gamma)$	396
			17.10.3	$B \rightarrow D^{(*)}\tau\nu$	404
			17.10.4	Discussion and future prospects	407
			17.11	Rare and forbidden B decays	410
C	The results and their interpretation	178			
16	The CKM matrix and the Kobayashi-Maskawa mech-				
	anism	178			
16.1	Historical background	178			
16.2	CP violation and baryogenesis	180			
16.3	CP violation in a Lagrangian field theory	180			
16.4	The CKM matrix	181			
16.5	The Unitarity Triangle	182			
16.6	CP violation phenomenology for B mesons	183			
17	B physics	185			
17.1	V_{ub} and V_{cb}	186			
17.1.1	Overview of semileptonic B decays	186			
17.1.2	Exclusive decays $B \rightarrow D^{(*)}\ell\nu$	189			
17.1.3	Inclusive Cabibbo-favored B decays	194			
17.1.4	Exclusive decays $B \rightarrow \pi\ell\nu$	200			
17.1.5	Inclusive Cabibbo-suppressed B decays	209			
17.1.6	Evaluation of the results	215			
17.2	V_{td} and V_{ts}	216			
17.2.1	$B_{d,s}$ mixing	216			
17.2.2	$B \rightarrow X(s, d)\gamma$	217			
17.2.3	Summary	219			
17.3	Hadronic B to charm decays	221			
17.3.1	Introduction	221			
17.3.2	Theory overview	221			
17.3.3	Decays with a single D decay (D, D^*, D_s)	225			
17.3.4	Decays with 2 D 's	227			
17.3.5	Decays to charmonium	232			
17.3.6	Summary	235			

17.11.1	$B^0 \rightarrow \ell^+ \ell^- (\gamma)$	410	19.2.3	Decays to CP eigenstates	573
17.11.2	$B^0 \rightarrow$ invisible	413	19.2.4	t -dependent Dalitz analyses	578
17.11.3	$B^0 \rightarrow \gamma\gamma$ and $B_s^0 \rightarrow \gamma\gamma$	414	19.2.5	Semileptonic decays	580
17.11.4	Lepton flavor violating modes	416	19.2.6	t -integrated CP violation measurements	584
17.11.5	Lepton number violating modes	418	19.2.7	t -dependent CP violating asymmetries	594
17.11.6	Lepton/baryon number violating modes	420	19.2.8	Summary	596
17.11.7	Summary	421	19.3	Charmed meson spectroscopy	599
17.12	B decays to baryons	422	19.3.1	Introduction	599
17.12.1	Inclusive decays into baryons	422	19.3.2	Production of charmed mesons at B Fac- tories	604
17.12.2	Two-body decays	423	19.3.3	Non-strange charm spectroscopy	604
17.12.3	Decays to baryon antibaryon plus mesons	428	19.3.4	Charmed-strange mesons	610
17.12.4	Radiative decays into baryons	439	19.3.5	Conclusions	622
17.12.5	Semileptonic decays with a baryon-antibaryon pair	440	19.4	Charmed baryon spectroscopy and decays	623
17.12.6	Summary	440	19.4.1	Spectroscopy	623
18	Quarkonium physics	441	19.4.2	Weak decays	631
18.1	Introduction to quarkonium	441	19.4.3	Applications to light baryon spectroscopy	635
18.1.1	Quantum numbers and spectroscopy	441	20	Tau physics	637
18.1.2	Potential models	442	20.1	Introduction	637
18.1.3	Quarkonium as a multiscale system	443	20.2	Mass of the tau lepton	637
18.1.4	Effective Field Theories	444	20.3	Tests of lepton universality	639
18.1.5	Lattice calculations	447	20.3.1	Charged current universality between μ - e	639
18.1.6	Applications	447	20.3.2	Charged current universality between τ - μ	640
18.2	Conventional charmonium	449	20.4	Search for lepton flavor violation in tau decays	640
18.2.1	New conventional charmonium states	449	20.4.1	Tau lepton data samples and search strate- gies	640
18.2.2	New decay modes of known charmonia	457	20.4.2	Results on LFV decays of the tau from Belle and BABAR	642
18.2.3	Measurements of parameters	459	20.4.3	Future Prospects	644
18.2.4	Production	462	20.5	CP violation in the tau lepton system	644
18.2.5	Concluding remarks	468	20.5.1	Electric dipole moment of the tau lepton	645
18.3	Exotic charmonium-like states	469	20.5.2	CP violation in tau decay	648
18.3.1	Theoretical models	469	20.6	Hadronic tau decays	651
18.3.2	The $X(3872)$	470	20.6.1	Theory	651
18.3.3	The 3940 family	476	20.6.2	Tau lepton branching fractions	655
18.3.4	Other $C = +1$ states	477	20.6.3	Hadronic spectral functions: Cabibbo- favored modes	655
18.3.5	The 1^{--} family	478	20.6.4	Hadronic spectral functions: Cabibbo- suppressed modes	659
18.3.6	Charged charmonium-like States	480	20.6.5	Inclusive non-strange spectral function	660
18.3.7	Summary and outlook	482	20.6.6	Inclusive strange spectral functions	660
18.4	Bottomonium	485	20.6.7	Search for second-class currents	661
18.4.1	Introduction	485	20.7	Tests of CVC and vacuum hadronic polariza- tion determination	662
18.4.2	Common techniques	485	20.7.1	CVC and vacuum hadronic polariza- tion contribution in $(g - 2)_\mu$	663
18.4.3	e^+e^- energy scans	486	20.7.2	CVC and $\pi\pi$ branching fraction	664
18.4.4	Spectroscopy	487	20.8	Measurement of $ V_{us} $	664
18.4.5	Discovery of charged Z_b states	496	20.9	Summary of the tau section	665
18.4.6	Transitions and decays	498	21	Initial state radiation studies	667
18.4.7	Physics beyond the Standard Model	506	21.1	Introduction	667
19	Charm physics	515	21.2	The Initial State Radiation method	667
19.1	Charmed meson decays	516	21.2.1	Radiator function and Monte Carlo gen- erators	668
19.1.1	Introduction	516	21.2.2	Cross section	669
19.1.2	Branching ratio measurements	520	21.2.3	Mass resolution and energy scale	670
19.1.3	Cabibbo-suppressed decays	524	21.2.4	Comparison of tagged and untagged ISR measurements with direct e^+e^- mea- surements	671
19.1.4	Dalitz analysis of three-body charmed meson decays	530	21.3	Exclusive hadronic cross-sections	672
19.1.5	Semileptonic charm decays	543			
19.1.6	D_s^+ leptonic decays	551			
19.1.7	Rare or forbidden charmed meson decays	554			
19.1.8	$D^0 \rightarrow \ell^+ \ell^-$	555			
19.1.9	Search for rare or forbidden semilep- tonic charm decays	558			
19.1.10	Summary of charmed meson decays	560			
19.2	D -mixing and CP violation	561			
19.2.1	Introduction	561			
19.2.2	Hadronic wrong-sign decays	567			

