Planned Measurements of CP–violation at BaBar

Workshop on CP Violation
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Reporting on the work of 634 others

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- Anders Ryd — California Institute of Technology
- High Energy Physics Lab — Harvard University

Objective

The question of how to use BaBar to best study CP violation is a large question, certainly too large for a single talk. The question requires both experimental considerations, like expected rates for identified and reconstructed classes of events, and theoretical considerations, like how to extract fundamental Standard Model parameters from experimental results when the relationships between the two are clouded by uncertainty, e.g., uncertainty in hadronic processes.

This presentation focuses on the experimental portion of the problem by giving a status report on BaBar and by explaining how BaBar contributes to the study of CP violation.

We begin with basic theoretical context to determine what must be measured, thereby motivating the basic detector needs. After describing the detector and giving construction status, we show a strawman analysis for a few of the simplest CP modes. In doing so, we present analysis techniques and expand upon key issues like tagging. Where appropriate, comments about CP reach are made.

OVERVIEW

- **Objective**
- **Theoretical Context**
- **Detector Status**
- **Basic CP modes**
- $B^0 \to J/\psi\, K^0_S$
- **Tagging and PID Revisited**
- $B^0 \to J/\psi\, K^0_L$
- $B^0 \to \pi^+\pi^-$
- **Schedule**
- **Conclusions**

Theoretical Context

A sketch of CP violation:

1. CP is not a good symmetry if $(CP)^\dagger\ H\ (CP) \neq H$
2. The CP transform of H causes coefficients, e.g., coupling constants, to become complex conjugated.
   - If there are coefficients with essential phases, then the SM admits CP violation via interference between terms with relative phases that change under CP conjugation.
3. The CKM matrix for 3 quark generations allows one complex phase and so allows CP violation.
   - Matrix can be parameterized by 4 real numbers, A, λ, $(\rho+i\eta)$
   - If η is non-zero, there are many CP violating processes.
4. Experimental question: Given observations of the many processes, can they *all* be fit quantitatively and *simultaneously* by just those 4 parameters?
   - The problem is over constrained and thus allows stringent tests.
   - Non CP processes are important.

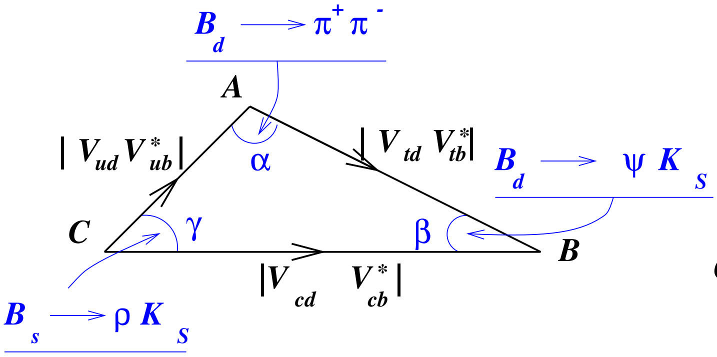
CKM Matrix

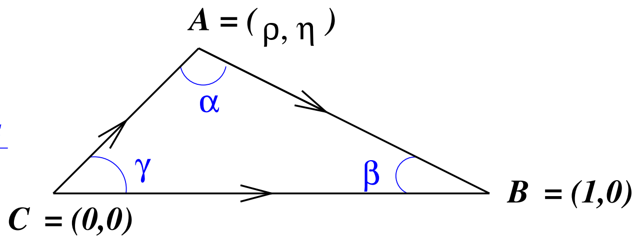
- Relates weak and mass eigenstates for quarks.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Unitarity triangle and decays





Example: $B^0 \to J/\psi\, K_S^0$

To motivate the detector requirements:

- Measuring the time dependent rate for $B^0 \to J/\psi\, K_S^0$ and, separately, the rate for $\overline{B}^0$ gives $\sin 2\beta$.

  $$\frac{\Gamma(B^0\to J/\psi\, K_S^0)-\Gamma(\overline{B}^0\to J/\psi\, K_S^0)}{\Gamma(B^0\to J/\psi\, K_S^0)+\Gamma(\overline{B}^0\to J/\psi\, K_S^0)} = -\sin 2\beta \sin \Delta M t$$

- Must measure time.
  - Separation in time via separation in space.
- Must identify B^0 vs. $\overline{B}^0$ by examining decay products
  - Called *Tagging.*
  - Uses sign of daughter K or lepton.

Deduce essential requirements for the experiment

- Boosted CM to separate B^0 from $\overline{B}^0$ in space ($c\tau = 449\,\mu$m)
- Precision vertexing and tracking to measure that separation.
- Particle ID to do tagging and reduce backgrounds.
- Precise and efficient calorimeter. ($\pi^0$are important.)
- High luminosity. (small branching fractions.)

The BaBar Detector at the SLAC B-Factory (PEP-II)

9 Countries
73 Institutions
634 Collaborators

USA
California Institue of Technology
UC, Irvine
UC, Los Angeles
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
U of Iowa
Iowa State U
LBNL
LLNL
U of Louisville
U of Maryland
U of Mass, Amherst
MIT
U of Mississippi
Mount Holyoke College
Northern Kentucky U
U of Notre Dame
ORNL/Y-12
U of Pennsylvania
Prairie View A&M
Princeton
Rutgers
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Dallas
Vanderbilt
U of Wisconsin

Canada
U of British Columbia
Carelton U and CRPP
McGill U
U de Montreal
TRIUMF
U of Victoria

Norway
U of Bergen

Russia
Budker Inst., Novo-sibirsk

China
Beijing Glass Research Inst.
Inst. of HEP, Beijing
Shanghai Inst. of Ceramics

France
LAPP, Annecy
LAL Orsay
LPNHE des Univ. Paris 6/7
Ecole Polytechnique
CEA, DAPNIA, CE-Saclay

Germany
Ruhr U Bochum
Technische U Dresden

Italy
INFN, Bari
INFN, Ferrara
Lab. Naz. di Frascati dell' INFN
INFN, Genova
INFN, Milano
INFN, Napoli
INFN, Padova
INFN, Pavia
INFN, Trieste
INFN, Pisa
INFN, Roma and U "La Sapienza"
INFN, Torino

UK
U of Bristol
Brunel U.
Edinburgh
Liverpool
Imperial Coll.
Queen Mary & Westfield
Royal Holloway & Bedford New Coll.
Manchester
Rutherford Appleton Laboratory

Status part of the talk...

Start with a simple schematic of the detector to come back to many times.

Give status of subsystems, one by one, walking outward in radius.

Say objective of each subsystem first.

Each subsystem will have a picture or two showing real hardware.

PEP–II: Features and Status

Features

- Configuration

Parameter	HER	LER	
Particle	e^-	e^+	
Beam Energy	9.000	3.109	GeV
Bunch Length	1.0	1.0	cm
Particles per Bunch	2.73	5.91	$\times 10^{10}$
Energy spread	5.5	2.5	MeV
CM Energy		10.580	GeV
$\beta\gamma$		0.56	
Peak Luminosity		3.0×10^{33}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Bunch Spacing		4.20	nsec

- Estimate of integrated luminosity:

In operation	9	mo/yr
Machine physics R&D	4	day/mo
Maintenance	2	day/mo
Average Luminosity	74%	of peak (hourly fill)
Beam tuning	1.5	hour/day
Operational Efficiency	76%	
Integrated Luminosity	30	fb^{-1}/yr ($\sim 30 \times 10^6 B^0\overline{B}^0$)

PEP–II: Features and Status

Status

- HER, LER, Injection, Controls, RF and Interaction Region are all complete.
- July dedicated to LER Commissioning.
- First collisions in the fall.
- Collisions with BaBar in April 1999.
- Detailed studies of machine backgrounds started in June '97 via a commissioning IR and various dedicated commissioning detectors.

Silicon Vertex Tracker (SVT): Features and Status

Tasks

- B^0–$\overline{B}^0$ vertex separation.
- Track *finding* for p_{T} below 100 MeV/c.
- Particle ID via dE/dx.

Features

- 5 layers (a pair of inner, a pair of outer, plus a middle)
- 300 μm thick, double sided Si wafers.
- Orthogonal ϕ, z measurements. 150,000 channels of Q and T.
- $-0.95 < cos\theta_{cm} < 0.87$.
- Point resolution: 10-15 μm inner, 30-40 μm outer layers.
- Timing via 67 ns clock.
- Tolerate 10$\times$ nominal radiation for 10 years.

Silicon Vertex Tracker (SVT): Features and Status

Status

- All Si wafers in hand
- All fanouts in hand
- Both batches of AToM chips in hand. Start testing second soon.
- Mechanical support and cooling is basically complete.
- Test module studied in test beam confirms design simulations.
- Start final assembly in August.
- Start cosmics in December at LBNL
- Begin mounting in support tube January, 1999.

Drift Chamber (DCH): Features and Status

Tasks

- Tracking reconstruction.
- Particle ID via dE/dx.
- Small radiation length (preserve σ_{p_T}, DIRC and EMC).

Features

- 7104 hex cells, $1.2 \times 1.8\ \mathrm{cm}^2$, typical.
- 10 superlayers of 4 layers: AUVAUVAUVA
- Helium-Isobutane (80% : 20%) gas.
- Thickness:

Inner Be cylinder	0.28%	X_0
Gas plus wires	0.3%	X_0
Outer cylinder	1.5%	X_0

- Find tracks down to p_T of $0.125\ \mathrm{GeV}/c$.
- Spatial resolution better than $140\ \mu\mathrm{m}$ in 1.5 T field.
- $\sigma_{p_\mathrm{T}} \sim 0.3\% \times p_\mathrm{T}$ above $1.0\ \mathrm{GeV}/c$.
- dE/dx resolution of 7%
- $20\ \mathrm{MeV}/c^2$ for $B^0 \to \pi^+\pi^-$, $5\ \mathrm{MeV}/c^2$on $B^0 \to D^+D^-$.

Drift Chamber (DCH): Features and Status

Status

- Performance confirmed by full-length prototype.
- Stringing completed last December.
- Tested with He–Isobutane gas: noise was low.
- Chamber shipped to SLAC.
- 100% good wires.
- Gas system is complete and is at SLAC.
- Readout chip production and testing is complete.
- Front–end assembly (FEA) production is ongoing.
- Chamber will be installed in August.

DIRC: Features and Status

DIRC = **D**etection of **I**nternally **R**eflected **C**herenkov light

Tasks

- K/π identification, even at 4.0 GeV/c and large dip angle.
- Needed for tagging and reconstruction.
- Measures Cherenkov angle, given a reconstructed DCH track.
- Uses cylindrical arrangement of quartz bars (n=1.472).

Features

- 11,000 2.82 cm PMT used to reconstruct Cherenkov angle.
- 14% X_0.
- Covers 87% of polar angle, 93% of ϕ in CM frame.
- K efficiency > 95% with π misID < 3%, up to 3 GeV/c.
- 95% becomes 97% for $B^0 \to K^+\pi^-$.
- μ efficiency > 80% below 750 MeV/c, 95% below 500 MeV/c.

DIRC: Features and Status

Status

- Standoff box (holds PMTs and water) complete and leak tested.
- Support structure (Strong support tube, horse collar), and the magnetic shielding are done and are in the hall.
- The light cylinder (central support tube) is in IR-12.
- All the quartz ingots (raw material) are in hand.
- All front-end electronics are in hand and function well.
- The 10,752 photomultipliers are mounted on the Sob, cabled and tested in IR-6. Only five of them are noisy or dead.
- Further leak tests, and PMT tests (including cosmic tests) are in progress.

EM Calorimeter (EMC): Features and Status

Tasks

- High efficiency for low energy photons.
- E and Angle resolution: improve π^0 and B^0 mass resolutions.
- Reconstruct π^0
- Lepton ID: e/π, μ/π, e/μ.

Features

- CsI(Tl) crystals. Quasi-projective geometry
- Barrel (5760 crystals) plus forward endcap (820 crystals)
- $-0.916 \leq cos\theta \leq 0.895$ in CM
- Minimum detectable energy for photons $\sim$ 10–20 MeV.
- $\frac{\sigma_E}{E} = 1\%/\sqrt[4]{E} \oplus 1.2\%$
- $\sigma_{\theta,\phi} = 3\,\mathrm{mr}/\sqrt{E} \oplus 2\,\mathrm{mr}$
- Crystal length between $16.1X_0$ and $17.6X_0$.
- Radioactive source calibration system. (^{16}N, 6.1 MeV)

EM Calorimeter (EMC): Features and Status

Status

- Support cylinder complete and all crystal modules are loaded, aligned, and electrically tested.
- Cabling and cooling complete.
- RF shielding complete.
- Install barrel in solenoid by 9 July.
- Circulating source (calibration) panels complete. Install in Aug/Sept.
- All on–detector electronics in hand. Still need readout modules.
- Endcap construction well along.
- DAQ electronics, Calibration system, light pulser commissioning in October.
- Cosmics in November.

Muon and Neutral Hadron Detector (IFR): Features and Status

IFR = **I**nstrumented **F**lux **R**eturn

Tasks

- μ/π identification.
- K_L^0 detection

Features

- Resistive Plate Chambers (RPC) interleaved with layers of iron forming the magnet yoke.
- Barrel plus endcaps: cover $-0.921 \leq \cos\theta \leq .955$ (Lab)
- 21 Barrel layers, 18 Endcap layers
- Argon-Freon 134A gas mixture.
- RPC read out in two orthogonal views (per layer).

Status

- All RPC's constructed, tested and inserted in flux return
- Cylindrical (inner) RPC to be inserted in July.
- Gas system done.
- FE Electronics mounting underway as is cabling.

Other Systems: Features and Status

Other important systems not discussed in detail:

- Magnet
- Electronics
- Trigger
- Computing

Basic CP Modes

I want to communicate an estimate of our precision for studying CP violation. This precision is determined by

- Sample sizes
  - Integrated luminosity and cross section.
  - Branching ratios.
- Reconstruction efficiency and resolution
- Physics
  - Fraction of sample that can be tagged.
  - Physics backgrounds.
- Theory
  - Extracting SM parameters from experimental results.

First we enumerate the important processes for studying CP violation and then outline how the data could be analyzed. The latter is used to motivate more detailed discussion of detector capabilities.

Enumeration of Basic CP Modes

Objective	Mode	Comments
$\sin 2\beta$	$B^0 \to J/\psi\, K_S^0$	Golden mode
	$B^0 \to J/\psi\, K_L^0$	cross check of K_S^0
$\sin 2\alpha$	$B^0 \to \pi^+\pi^-$	Isospin analysis
	$B^+ \to \pi^+\pi^0$	
	$B^0 \to \pi^0\pi^0$	
	$B^0 \to \rho^+\pi^-$	Isospin and Angular analysis
	$B^0 \to \rho^-\pi^+$	
	$B^0 \to \rho^0\pi^0$	
$\mid V_{cb} \mid$	$B^0 \to D^* l\nu$	
$\mid V_{ub} \mid$	$B \to \rho/\pi l\nu$	
$f_b \mid V_{ub} \mid$	$B^+ \to \tau^+\nu_\tau$	Rare

The last few entries are included to point out that there needs to be a general experimental program to support the CP violation studies, and there are modes where BaBar can contribute.

$B^0 \to J/\psi\, K_S^0$

- Very clean theoretically: easy to extract $\sin 2\beta$
- Measure time dependent asymmetry via dN/d(Δz).

  $\Delta z \equiv s[z_{CP}$ - $z_{Tag}]$

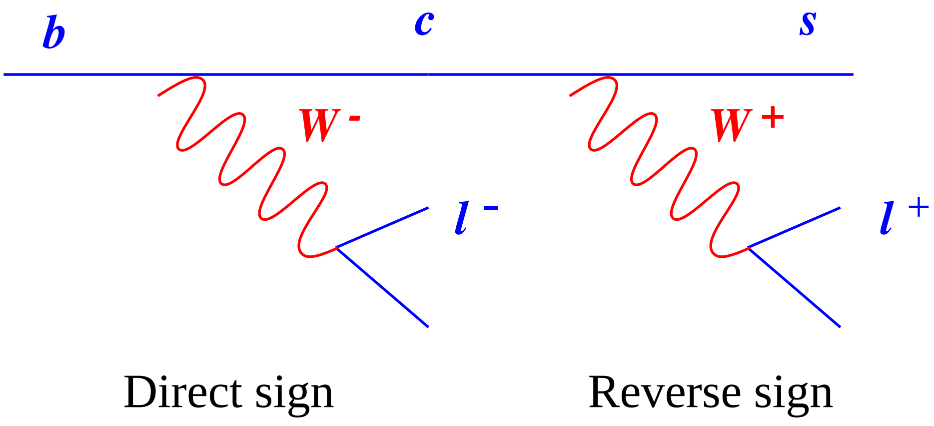
  dN/d(Δz) $= N_0 e^{-\Gamma_z|\Delta z|}[1 + \sin(2\beta)\sin(\Delta M \Delta z)]$.
- Decay modes considered:

  $J/\psi \to e^+e^-$ or $\mu^+\mu^-$ $\quad K_S^0 \to \pi^+\pi^-$
- Form J/ψ from charged track pairs w/ 1 loose lepton ID cut.
- Form K_S^0 from charged track pairs fit under π hypothesis.
- Form B^0 from candidates above and apply mass cut.
- Cut on B^0 momentum in Υ(4S) rest frame.
- Remaining tracks give B^0 tag and tag vertex (more later).
- BG from $B^0 \to J/\psi\, X$, SL decay of b,c or $q\overline{q}$ w/ J/ψ.
  - BG $< 6\%$.
- $\delta(\Delta z) \sim 150\ \mu$m.
- $\delta(\sin 2\beta)$= 0.12 in 30 fb^{-1} when $\sin 2\beta = 0.7$.
- $\delta(\sin 2\beta)$= 0.30 in 30 fb^{-1} for $K_S^0 \to \pi^0\pi^0$.

Tagging

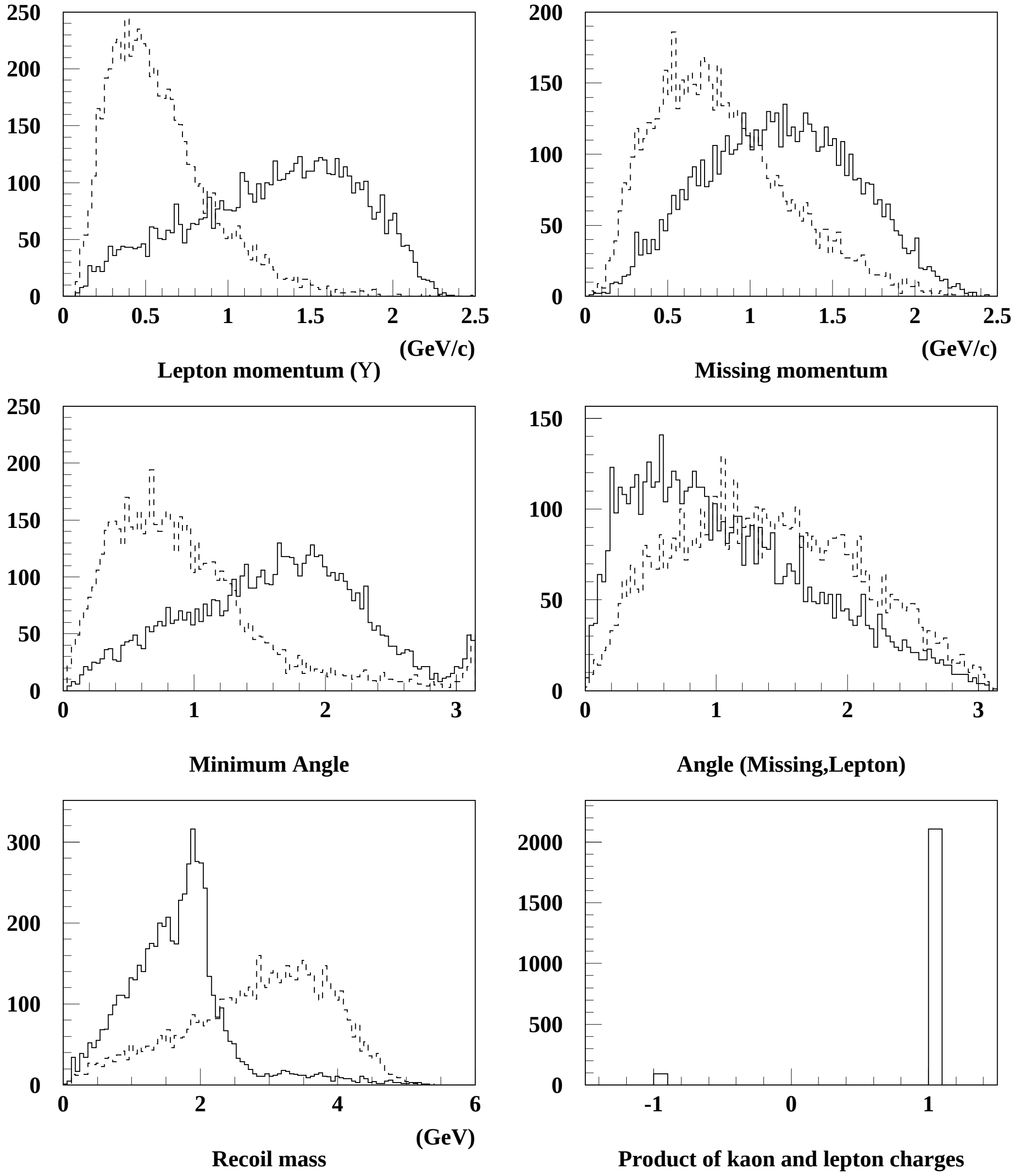
Tagging determines the quark content (b or $\overline{b}$) of a B meson.

- Sign of daughter determines b vs. $\overline{b}$.



  - Daughter can be a lepton or a kaon.
- Direct daughters are higher in momentum than indirect.
- Use momentum and other variables to choose b–quark charge.
- Use multi–variate discriminant analysis.
- NOTE: this is where PID comes in.
- Performance
  - $\epsilon_{Tag}(1-2w)^2 = 23\%$ with early PID tools.
  - Perfect PID would give 35%.
  - Analyses here use 30% since we know we can do better PID.

Illustration of tagging variables.



Tag–Side Vertex

- Tag–side Vertex
  - Use tracks left over from the fully reco'd CP side.
  - Select tracks
    * Impact parameter cut: Avoid tracks from secondaries.
    * Angle cut: use fiducial volume for good tracking.
  - Combine the rest into a vertex
    * May fail, e.g., only 1 track.
    * Apply cuts to improve resolution, e.g., on invariant mass, χ^2.
  - Find best primary track
    * Search amongst PID outputs.
    * For leptons, use momentum cuts to bias out secondaries.
    * Z is distance of closest approach to beam axis.
  - Combine vertex and primary track Z information.
- Performance
  - Resolution
  - Efficiency

Particle ID

- PID is done in several subsystems:

SVT and DCH	dE/dx
DIRC	Cherenkov angle or veto
Calorimeter	shower shape or E/p
IFR	Shower shape

- Sample of predicted performances (work in progress):

Type	Momentum	System	Eff.	MisID	Comments
K/π	p < .700 GeV/c	SVT	85%	1%	
		DCH	53	2	
	p > .700	DIRC	93	2.5	Half of K tags.
	p < .460	DIRC Veto	50	7	
	Tagging		78	4.5	w/ acceptance.
	Tight selection		58	0.6	
p/π	p < 1.4	dE/dx	90	3	
p/K	p < 1.0	dE/dx			
e/π		EMC E/p	96	0.2	
π^0/γ	$2 < p < 3$	EMC shape	95	3	

$$B^0 \to J/\psi\, K_L^0$$

K_S^0 and K_L^0 have opposite CP eigenvalues.

- Asymmetry equal, but opposite in sign, to K_S^0 case.
  - Test of systematics.
- Reconstruct J/ψ as before.
- K_L^0 observed in IFR: direction, but not momentum.
  - Direction good to 30 mr.
  - Fewer constraints, so more background.
  - Search for K_L^0 back-to-back with J/ψ. (300 mr)
  - Use J/ψ momentum and B^0 mass to compute $\mid p_{K_L^0} \mid$
- p_B^* obtained with $\sigma \sim 69\,\mathrm{MeV}/c$.
  - 51 MeV/c from K_L^0 direction.
  - 47 MeV/c from beam energy spread.
  - Accept only $p_B^* < 450\,\mathrm{MeV}/c$
- BG from B^0 and B^+ decays and combinatorial BG.
  - 59% (but there are tricks that might reduce it)
- $\delta(\sin 2\beta) = 0.136$ to 0.145 in $30\,\mathrm{fb}^{-1}$.

Other $\sin 2\beta$ modes

Other modes have been studied. Work is ongoing, but the following have been examined and an estimate of $\delta(\sin 2\beta) \sim 0.069$ is obtained for $30\,\mathrm{fb}^{-1}$ after combining them. The clean $J/\psi\, K_L^0$ and $J/\psi\, K_S^0$ modes dominate the precision.

$J/\psi\,(l^+l^-)K_S^0(\pi^+\pi^-)$

$J/\psi\,(l^+l^-)K_S^0(\pi^0\pi^0)$

$J/\psi\,(l^+l^-)K_L^0$

$\psi'(\pi^+\pi^-l^+l^-)K_L^0$

$\chi_{c1}(\gamma l^+l^-)K_L^0$

$J/\psi\,(l^+l^-)K^{*0}(\pi^+\pi^-\pi^0)$

$J/\psi\,(l^+l^-)K^{*0}(\pi^0\pi^0\pi^0)$

D^+D^-(6 D Modes)

$D^{*+}D^{*-}$(6 D Modes)

$\phi(K^+K^-)K_L^0$

$\phi(K^+K^-)K^{*0}(\pi^+\pi^-\pi^0)$

$\eta'(\eta\pi^+\pi^-)K_S^0(\pi^+\pi^-)$

$\eta'(\rho\gamma)K_S^0(\pi^+\pi^-)$

$\eta'(\eta\pi^+\pi^-)K_L^0$

$B^0 \to \pi^+\pi^-$

- Time dependent asymmetry is related to $\sin 2\alpha$.
- Contribution from penguins may degrade precision on $\sin 2\alpha$.
- Isospin analysis might recover $\sin 2\alpha$. Must measure many modes:

$$\begin{array}{lll} B^+ \to \pi^+\pi^0 & B^0 \to \pi^+\pi^- & B^0 \to \pi^0\pi^0 \\ B^- \to \pi^-\pi^0 & \overline{B}^0 \to \pi^+\pi^- & \overline{B}^0 \to \pi^0\pi^0 \end{array}$$

- Branching fractions small. ($8\times10^{-6}, 1\times10^{-5}, 3\times10^{-6}$ assumed)
- $\pi^+\pi^-$: just combine oppositely charged tracks.
  - Backgrounds:
    - Continuum $q\overline{q}$ combinatorial backgrounds.
    - $B^0 \to K^+\pi^-$ with K^+ misid'd.
    - Combinatorial BG from generic $B^0\overline{B}^0$ negligible.
  - BG rejection:
    - Kinematic cuts: B^0 mass, B^0 momentum, π momentum.
    - PID to reject BG from $K^+\pi^-$.
    - Vertexing, Event shape, Flavor tag.
  - Acceptance=0.62, S/N=135/124

$B^0 \to \pi^+\pi^-$ **(cont'd)**

- $\pi^0\pi^0$: Really hard.
  - Pure calorimeter analysis.
  - π^0 is energetic: seen as single cluster. m_{π^0} not attempted.
  - Take cluster pairs, boost to Υ(4S), compare with $m_{\Upsilon(4S)}/2$
  - Multivariate analysis to control combinatorial BG.
  - Acceptance=0.15, S/N=14/18
- $\pi^+\pi^0$: Almost the same as $\pi^0\pi^0$.
  - Acceptance=0.19, S/N=50/90
- CP extraction and Isospin analysis
  - Maximum likelihood fit of Δz distribution.
  - Form isospin triangle to extract the shift in α.
  - Four–fold ambiguity.
  - Need 90 fb^{-1}to get anywhere.
- Reach for 90 fb^{-1}.

$B^0 \to \pi^+\pi^-$	$a_1, a_2, corr(a_1, a_2)$	$0.15, 0.18, .12$
$B^+ \to \pi^+\pi^0$	ΔBR/BR	.15
$B^0 \to \pi^0\pi^0$	ΔBR/BR	.3

- $P \sim exp(- \mid \Delta t \mid / \tau)(1 + a_1 \sin(\Delta M \Delta t) a_2 \cos(\Delta M \Delta t))$

Other $\sin 2\alpha$ modes

Other modes have been studied. Work is ongoing, but the following have been examined.

$B^- \to \eta h^-$ (h=K/π)

$B^0 \to \rho^+\pi^-$

$B^0 \to \rho^-\pi^+$

$B^0 \to \rho^0\pi^0$

$B^+ \to \rho^+\pi^0$

$B^+ \to \rho^0\pi^+$

$B^0 \to a_1^+\pi^-$

$B^0 \to a_1^-\pi^+$

$B^0 \to a_1^0\pi^0$

$B^+ \to a_1^+\pi^0$

$B^+ \to a_1^0\pi^+$

$B^0 \to \rho_0\rho_0$

$B^0 \to \rho_+\rho_-$

$B^+ \to \rho_+\rho_0$

Schedule

Near term schedule:

September	Assembly of BaBar in hall.
Nov. to mid–Dec.	Cosmic ray commissioning.
January	Begin installation onto beamline.
March	Checkout of full detector on the beamline.
April	Physics running.

Summary and Conclusion

- Expect to start on schedule.
- Analysis of a few decay modes were shown in some detail.
  - Many analysis tools exist and are being improved.
  - But, need real data to make choices.
- CP Reach shown for a few modes.
  - Many other modes are even harder.
  - Remember: goal is not just to measure the CKM parameters, but to measure them as many ways as possible to see if various modes are mutally consistent.
- Large samples and an experimental program to *explore* the realm of CP violating decays is needed, along with an active development of theory so as to interpret the results in terms of the SM.
- The footrace between BaBar and Belle is stimulating and constructive, but ultimately the overall success will come from collaboration on resolving physics questions.