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The Direct CP Violation Measurement at the BaBar Experiment

Summary

- Introduction to CP Physics
- The BaBar detector
- The CP Measurement
- Results
- Conclusions

CP Physics

Introduction

- The CP violation was discovered in 1964 studying the K^0 decays.
- The Standard Model with 3-quark generations can accomodate CP violation fixing the phase of the mixing mass matrix (CKM).
- In this way the model (SM) can predict the amount of CP violation in the B system.
- This measurement is a very significant test of the Standard Model.
- Any inconsistency among the measurements can be an indication of the new physics beyond the Standard Model.

The time evolution in the $B_0 - \overline{B_0}$ system

- The light B_L and heavy B_H eigenstates are given by

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

with

$$|p^2| + |q^2| = 1$$

- If the amplitudes of the B^0 and $\overline{B}^0$ to CP eigenstate f_{CP}

$$A \equiv \langle f_{CP}|\mathcal{H}|B^0\rangle, \quad \overline{A} \equiv \langle \overline{f_{CP}}|\mathcal{H}|\overline{B}^0\rangle$$

The parameter

$$\lambda_{CP} \equiv \frac{q}{p}\frac{\overline{A}}{A}$$

is related to parameters of the CKM matrix.

- One important test of CP Violation is the measure of the asymmetry:

$$a_f(t) = \frac{\Gamma(B^0(t) \to f) - \Gamma(\overline{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\overline{B}^0(t) \to f)}$$

which can be written in function of λ_{CP} as:

$$a_f(t) = \frac{(1 - |\lambda_{CP}|^2) cos(\Delta M_{B^0} t) - 2 Im \lambda_{CP}(f) sin(\Delta M_{B^0} t)}{1 + |\lambda_{CP}(f)|^2}$$

If all the amplitudes which contribute to the decay channels have the same weak phase, then $|\lambda| = 1$ and the above expression can be written as:

$$a_f(t) = -Im \lambda_{CP}(f) sin(\Delta M_{B^0} t)$$

where $t = t_{f_{CP}} - t_{tag}$

- At a B factory the B^0 and $\overline{B}^0$ mesons are produced in a coherent $L = 1$ state. Until one particle decays, there is always exactly one B^0 and one $\overline{B}^0$ present. However once one of the particles decays the other continues to evolve and there are possible events with two B^0 or two $\overline{B}^0$ decays.The probability is governed by the time between the two decays.

3 different types of CP Violation

- CP violation in decay. It occurs when the amplitude for a decay and its CP-conjugate process are different.

$$|\overline{A}_{\overline{f}}/A_f| \neq 1 \Longrightarrow CP \quad violation$$

- CP violation in mixing. It occurs when the two neutral mass eigenstates cannot be chosen to be CP-eigenstates

$$|q/p| \neq 1 \Longrightarrow CP \quad violation$$

- CP violation in interference. It occurs when the decay with and without mixing can interfere because the final states are common to B^0 and $\overline{B}^0$. Even with $\frac{|q|}{|p|} = 1$ and $\frac{|\overline{A}|}{|A|} = 1$ yon can have:

$$\lambda \neq \pm 1 \Longrightarrow CP \quad violation$$

CP Violation in the Standard Model

- In the Standard Model the relation between the flavour eigenstate and the mass eigenstate is described by the CKM matrix:

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

- A useful parameterization of the CKM matrix was given by Wolfenstein as power serie expansion of $\lambda = \cos\theta_{Cabibbo} \simeq 0.22$:

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- There are 4 real parameters A, λ, ρ, η, the last one is responsible for CP violation.
- It can be shown that in the Standard Model the amplitude of all the processes violating CP are proportional to:

$$J_{CP} \simeq A^2\lambda^6\eta$$

- The unitarity of V_{CKM} implies various relations among its elements. The most useful to understand the SM predictions for CP violation is:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Taking into account that $V_{ud} \simeq V_{tb} \simeq 1$ the previous relation can be rewritten as:

$$\frac{V_{ub}^*}{|V_{cd}V_{cb}|} + \frac{V_{td}}{|V_{cd}V_{cb}|} = 1$$

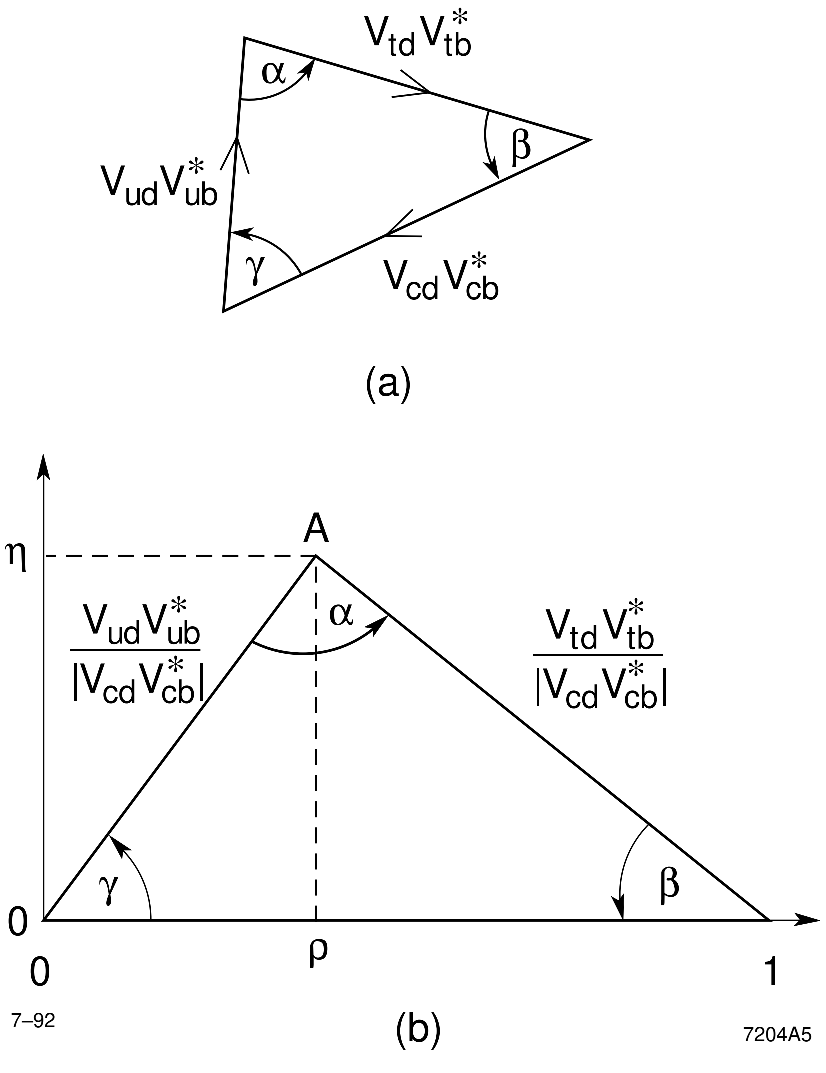
which can be represented as a triangle in the complex plane.

- The three angle of the unitarity triangle are denoted α, β, γ:

$$\alpha \equiv arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \beta \equiv arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \gamma \equiv arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

- In order to constrain the Standard Model all the angles (CP asymmetries) and the sides (rare decays) of the triangle must be measured. This is a very ambitious experimental program.

The Unitarity Triangle



CP Violation beyond the Standard Model

- The amount of CP violation foreseen in the Standard Model is not enough to explain the large imbalance of matter antimatter in the Universe. This suggest that new sources of CP violation can be found beyond the Standard Model.
- The presence of new physics could be observed through the violation of unitarity relation

$$\alpha + \beta + \gamma = 180^0 .$$

  Another way to observe the same phenomena is to find that the sides of the unitarity triangle do not agree with the measurement of angles.
- No tree level effects are expected because CKM-allowed diagrams are highly suppressed by $\mathcal{O}(M_W^2/\Lambda^2)$, where Λ (TeV region) is the energy scale where the new physics should show up.

- To observe loop effects in $B^0 - \overline{B}^0$ mixing it is mandatory to measure the γ angle which is an experimental challenge.
- In penguin induced process like $b \to s$ it is possible to observe experimentally some violation of Standard Model.The relation

$$A_{CP}^{mix-ind}(B_d \to J/\psi K_s) = A_{CP}^{mix-ind}(B_d \to \phi K_s)$$

will be violated by the presence of new physics.

The Experimental limit of the CKM matrix elements

- Some recent data can be used to constrain the parameter of V_{CKM} within the theoretical framework of the Standard Model.
- Using the following input parameters:

A	0.823 ± 0.033
$\frac{\lvert V_{ub}\rvert}{\lvert V_{cb}\rvert}$	0.08 ± 0.02
Δm_d	$(0.472 \pm 0.018)ps^{-1}$
Δm_s	$> 10.2ps^{-1} 95\% C.L.$
m_t	$(168 \pm 6)GeV/c^2$
B_K	0.90 ± 0.09
$f_{B_d}\sqrt{B_{B_d}}$	$(220 \pm 40)MeV$
$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$	1.10 ± 0.07

which includes also the best theoretical calculation available, some authors have estimated some value for the angles of the unitarity triangle:

$$\sin(2\alpha) = -0.10 \pm 0.40$$

$$\sin(2\beta) = 0.68 \pm 0.10$$

$$\gamma = (64 \pm 12)^0$$

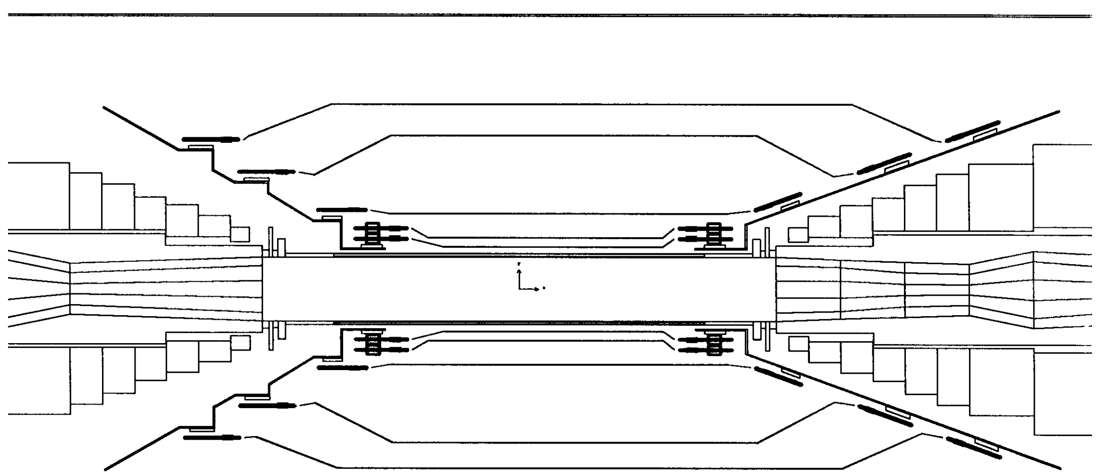
- If this indirect measure will be confirmed by the BaBar data the Standard Model will receive another beautiful confirmation, if not more interesting time is in front of us.

The BaBar detector

- In order to reconstruct the two primary B's and to measure the time interval between the two decays the main requirements of the BaBar detector are:
  - Large solid angle coverage, particular in the forward region
  - Vertex reconstruction with precision better of 80 μm
  - Momentum measurement up to $60 MeV/c$
  - Neutral energy reconstruction with good efficiency up to $20 MeV/c$
  - Good particle identification over the large momentum range
  - High trigger efficiency
- The components of BaBar are:
  - The Silicon Vertex
  - The Drift Chamber
  - The DIRC
  - The Electromagnetic Calorimeter
  - The IFR

The Silicon Vertex Tracker (SVT)

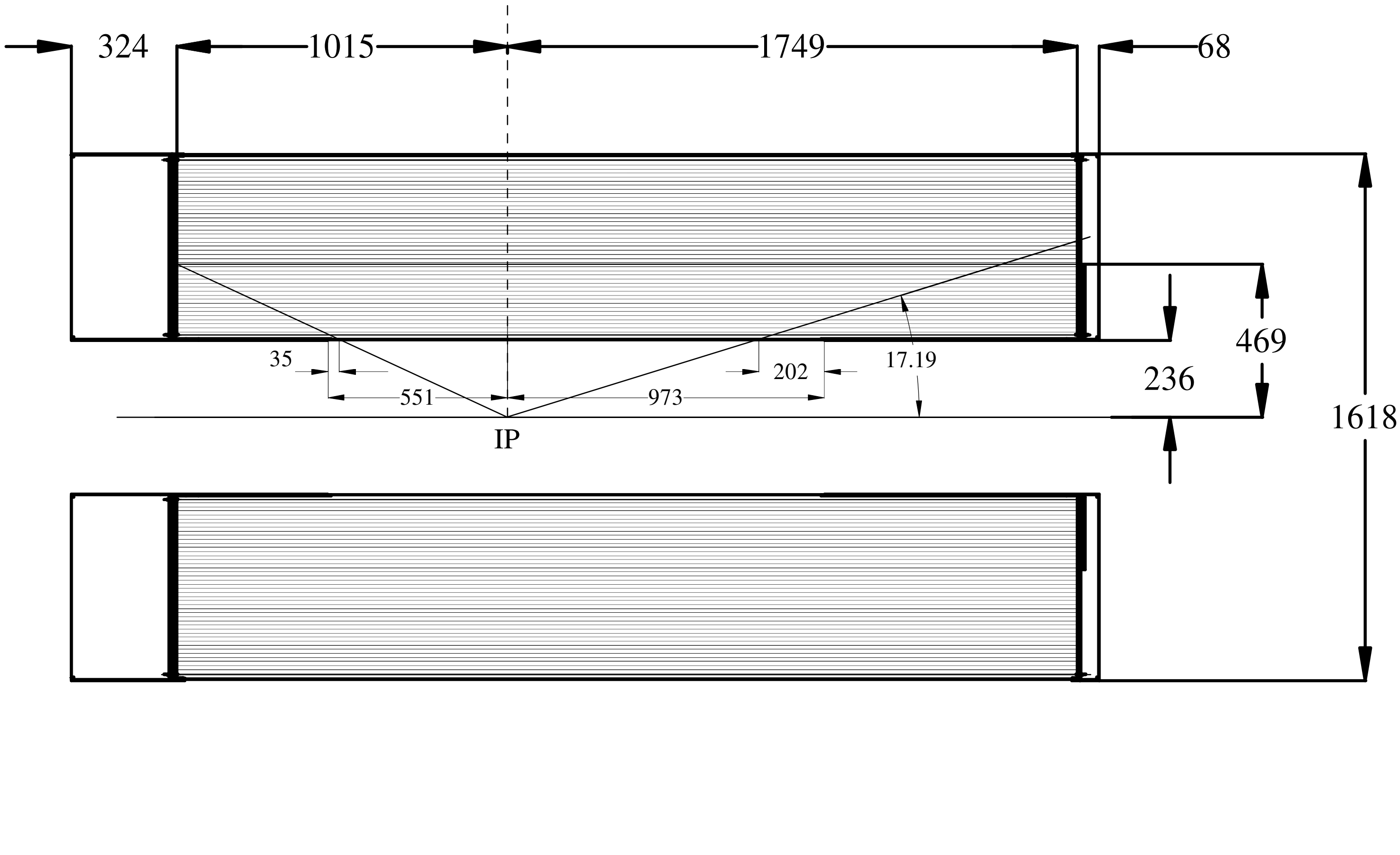
- The Vertex detector is made of 5 layers of double-sided silicon strips with radius between $2.5cm$ and $20cm$. The total amount of X_0 is 0.7%, and the detector is designed to be radiation hard.
- The other important feature are:
  - Pitch: $r - \phi = 50\mu m$, $z = 100\mu m$
  - $\sigma_z = 10\mu m$, $\sigma_{xy} = 10\mu m$



The Drift Chamber (DCH)

- The two main goals of this detector are the track reconstruction , together with the vertex detector, and the particle identification with the DIRC.
- It is a 280 cm long cylinder, with an inner radius of 23.6 cm and a outer radius of $80.9cm$.
- The drift cell are arranged in 40 layers, including Axial (A) and stereo (U, V) layers alternated with the following pattern AUVAUVAUVA.
- The gas used is Helium based to minimize multiple scattering.
- The resolution for track with $p > 1$ GeV/c is $\sigma_{p_t} \approx 0.3\% \times p_t$
- dE/dx resolution is 7% for 40 measurements
- The chamber will provide also track cluster information to be used for the first level trigger.

The Drift Chamber (DCH) picture

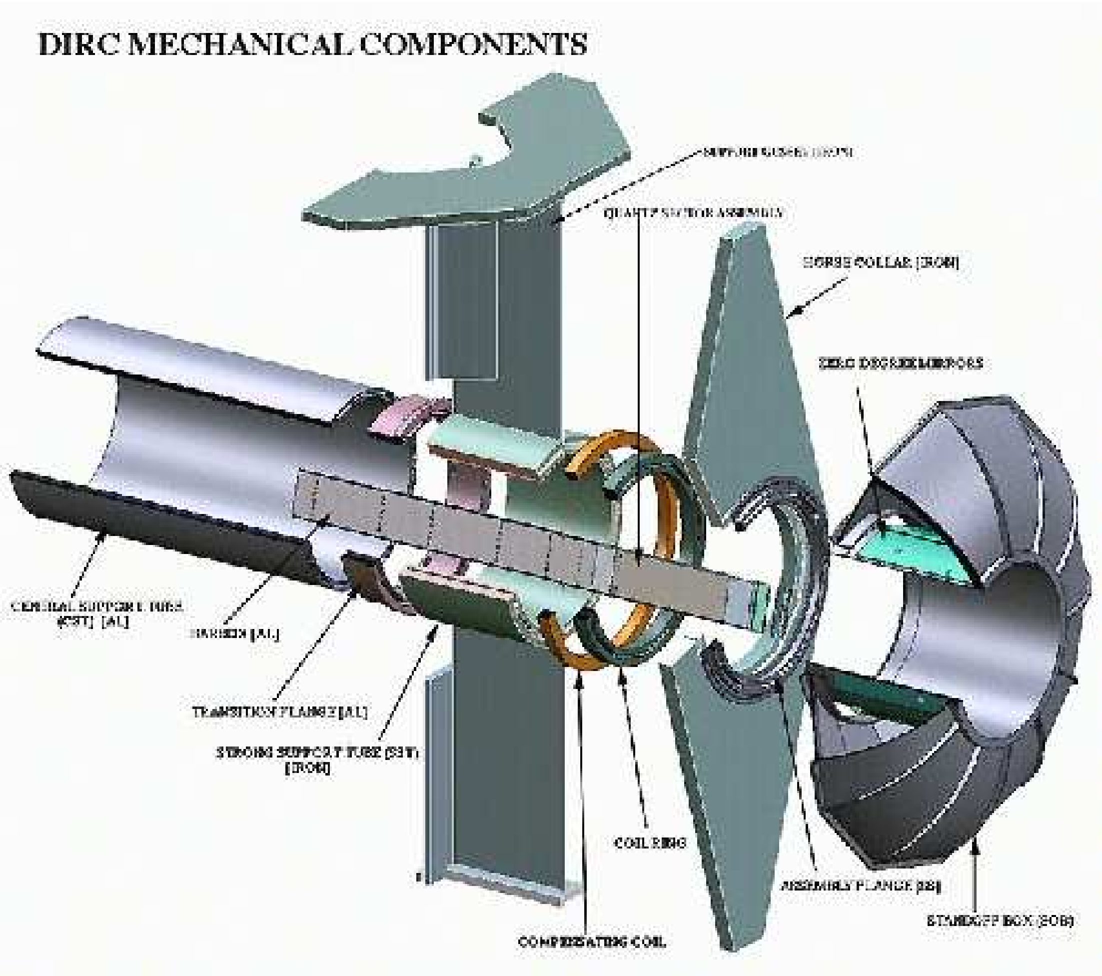


The DIRC

Detection of Internally Reflected Cherenkov light

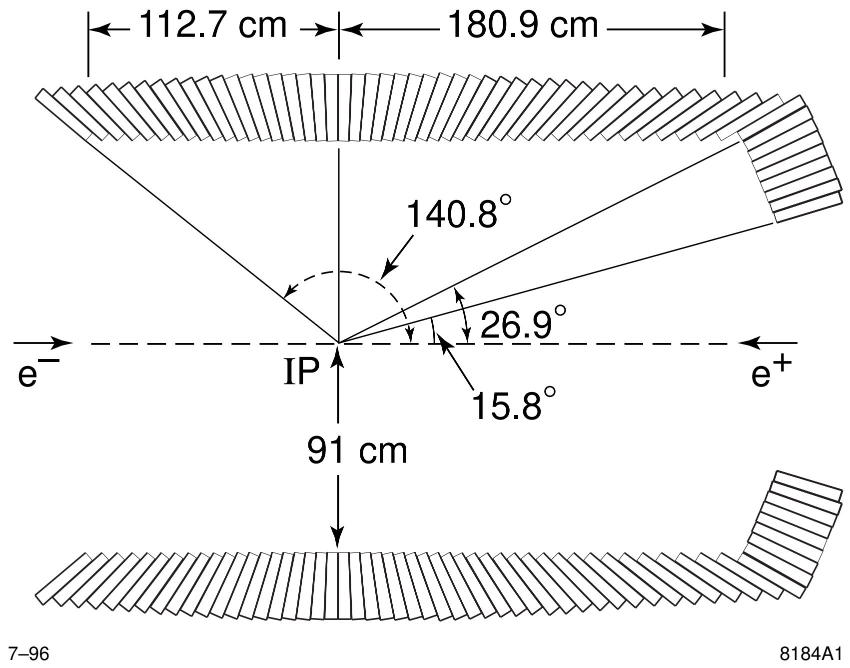
- This detector is the most original of BaBar because it has a very good light output in a very thin detector . It consists of 144 bars of synthetic quartz $(1.7 \times 3.5 \times 490 cm^3)$
- The light reflected at the backward end of the bars is collected by 11,000 PTM after a propagation in a purified water.
- The refractive index is close to 1.472
- π/K separation up to 2.5 GeV/c
- μ/π separation below 750 MeV/c

The DIRC Model



The Electromagnetic calorimeter (EMC)

Functional Overview



- One of the most important goal of BaBar is the electromagnetic energy reconstruction and the angular resolution.
- The choice of CsI(TL) crystal with photodiode readout and low

mass support structure, will guarantee good resolution down to $20 MeV$.

- The detector consists of 5760 crystals in the barrel and 900 crystals in the forward endcap (no calorimeter in backward endcap for budget reason.) The target energy resolution for photons at polar angle of 90^0 is:

$$\frac{\sigma_E}{E} = \frac{1\%}{\sqrt[4]{\mathrm{E(GeV)}}} \oplus 1.2\%$$

- The angular resolution is determined by the transverse crystal size and average distance to the interaction point. The target angular resolution of photons at a polar angle of 90^0 is:

$$\sigma_{\theta,\phi} = \frac{3\ \mathrm{mrad}}{\sqrt[2]{\mathrm{E(GeV)}}} + 2\ \mathrm{mrad}$$

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- The detector is ready to be installed inside the BaBar coil next week.

The Muon and Neutral Hadron Detector (IFR)

- The return yoke of the BaBar magnet will be used to measure the muons and to identify neutral hadrons (especially k_L^0). This will improve the tagging efficiency of the experiment.
- The detector consists of 19 layers (18 in the endcaps) of RPC chambers inserted in the graded iron.
- Good μ identification from .5 GeV/c
- Cylindrical RPC, double layer surrounding the EM calorimeter to help the μ tracking.
- π rejection at 2-3%.
- Thanks to the good time resolution of the RPC chambers it is possible to build a dedicated trigger (with muons or cosmics) and to measure the time arrival of beam particles (bunch crossing)
- The detector is installed and the barrel and is under DAQ test.

The Trigger

Two level trigger:
Level 1 hardware
Level 3 software after event assembly.

- The charged tack trigger requires at least 2 track in the drift chamber with $p_t > 0.18 GeV/c$ and $p_t > 0.12 GeV/c$
- The energy trigger requires in the electromagnetic calorimeter above a threshold that is efficient for muons.
- These selections produce a trigger rate of 16KHz which can be easily reduced to 2KHz with various correlation between energy and track cuts.
- The efficiency for golden CP events is expected to be close to 100%.
- The output rate of the level 3 trigger will be 100Hz. Preliminary studies have shown that the goal can be reached handling information of the full events without loosing any physics.

The determination of β

The decays can be classified in 3 types:

- Color suppressed modes $b \to c\bar{c}s$
  - $B_d \to J/\psi K_S^0$
  - no penguin contamination
  - no theoretical uncertainty
  - $Im\lambda() = sin2\beta$
- Cabibbo suppressed modes $b \to c\bar{c}d$
  - $B_d \to D\overline{D}, ...$
  - Penguin effects important
  - Analysis is still possible
  - $Im\lambda() = -sin2\beta$
- Penguin dominated mode $b \to s\bar{s}s$ or $b \to d\bar{d}s$
  - $B_d \to \pi^0 K_S^0 . \phi K_S^0, ..$
  - Penguin dominates
  - No clear theoretical understanding
  - $Im\lambda() \simeq -sin2\beta$

Table 0.1: Summary of $\sin 2\beta$ measurements assuming $\sin 2\beta$=0.7

Mode	(%)	Usable sample	Rec. eff.	N_S	N_B/N_S	$\sigma_{\Delta z}$		Tag factor	error
$J/\psi\,(\ell^+\ell^-)K^0_S(\pi^+\pi^-)$	0.0425	1089	0.60	653	0.06	130	1.61	0.3	0.12
$J/\psi\,(\ell^+\ell^-)K^0_S(\pi^0\pi^0)$	0.0425	499	0.21	104	0.06	130	1.61	0.3	0.30
$J/\psi\,(\ell^+\ell^-)K^0_L$	0.0425	1607	0.41	652	0.59	130	1.61	0.3	0.15
$\psi'(\pi^+\pi^-\ell^+\ell^-)K^0_L$	0.035	429	0.27	116	0.83	130	1.61	0.3	0.34
$1(\gamma\ell^+\ell^-)K^0_L$	0.050	516	0.28	143	0.78	130	1.61	0.3	0.28
$J/\psi\,(\ell^+\ell^-)K^{*0}(\pi^+\pi^-\pi^0)$	0.132	601	0.09	55	0.16	130	1.79	0.3	0.47
$J/\psi\,(\ell^+\ell^-)K^{*0}(\pi^0\pi^0\pi^0)$	0.132	300	0.05	15	>1	130	1.79	0.3	—
D^+D^- (6 D Modes)	0.045	664	0.24	144	2.80	130	1.61	0.3	0.48
$D^{*+}D^{*-}$ (4 D Modes)	0.097	1045	0.053	60	0.23	158	1.72	0.3	0.45
$\phi(K^+K^-)K^0_L$	0.00065	100	0.22	22	0.10	130	1.61	0.3	0.66
$\phi(K^+K^-)K^{*0}(\pi^+\pi^-\pi^0)$	0.001	26	0.20	5	<1	150	1.70	0.3	1.40
$\eta'(\eta\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.0024	88	0.23	20	0.10	150	1.70	0.3	0.73
$\eta'(\rho\gamma)K^0_S(\pi^+\pi^-)$	0.0024	155	0.35	55	0.90	130	1.61	0.3	0.56
$\eta'(\eta\pi^+\pi^-)K^0_L$	0.0024	206	0.21	44	0.10	150	1.70	0.3	0.49
Total error for 30 fb^{-1}									.069

- The precision of CP measurement can be expressed as:

$$\sigma(sin2\beta) = \frac{1}{d}\frac{\sqrt{1+B/N}}{\sqrt{\varepsilon N(1-2\omega)^2}}$$

  where

  - d = dilution = inverse of error of one event, it depends on $sin2\beta$, vertex resolution, $\Delta m/\Gamma$
  - ε = B flavour tagging efficiency
  - ω = mis-ID rate of B flavor tagging
  - N = # of events
  - B = # of background

- the result of the simulation and of different analysis is shown in the table. All the calculations are done for 1 year of data taking:

- $30 fb^{-1}$ will yield a precision of 0.069

Table 0.2: Summary of the studies of the two, three and four pion final states.

f	B_{tot}	ϵ	N_{tot}	B/S	δa_{cos}(f)	δa_{sin}(f)
$\pi^+\pi^-$	1.0×10^{-5}	0.39	135	0.9	0.29	0.26
$\pi^0\pi^0$	3.0×10^{-6}	0.15	14	2.5	-	-
$\pi^+\pi^0$	8.0×10^{-6}	0.19	50	2.0	-	-
$\rho^+\pi^- + \rho^-\pi^+$	5.4×10^{-5}	0.21	400	1.6	0.16	0.21
$\rho^0\pi^0$	1.0×10^{-6}	0.21	7	50	-	-
$\rho^0\pi^+$	1.1×10^{-5}	0.16	30	0.3	-	-
$\rho^+\pi^0$	2.6×10^{-5}	0.09	40	0.3	-	-
$a_1^+\pi^- + a_1^-\pi^+$	6.0×10^{-5}	0.12	124	1.7	0.23	0.34
$a_1^0\pi^0$	3.0×10^{-5}	0.07	72	13.3	-	0.47
$a_1^+\pi^0$	3.0×10^{-5}	0.042	43	3.0	-	-
$a_1^0\pi^+$	3.0×10^{-5}	0.044	23	4.6	-	-
$\rho^+\rho^-$	5.0×10^{-5}	0.15	263	5.3	-	0.28
$\rho^0\rho^0$	5.0×10^{-5}	0.22	377	6.7	-	0.17

The determination of α

- Studies done in $2\pi.3\pi, 4\pi$ modes
- Analysis methods to disentangle tree from penguin contribution have been applied (isospin analysis)
- Several decays mode must be studied, including charged decay modes.
- Results of simulation studies two, three, four pion modes are shown in the table
- Due to penguin contamination prediction of $\sin 2\alpha$ may require large integrated luminosity.

Conclusions

- The BaBar detector will be ready, this Fall, to take cosmic data with all the components installed except the vertex .
- In January 1999 BaBar will move in the beam line.
- After a year of data taking ($30 fb^{-1}$) the Standard Model prediction of CP violation in the B_0 system will be tested.