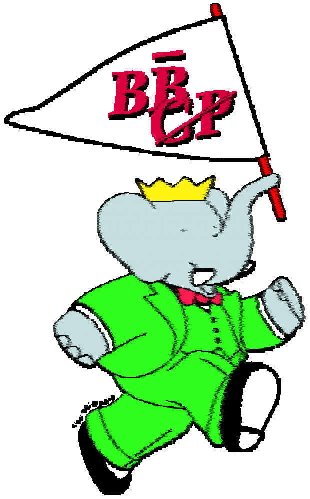
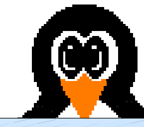




Penguin Approach to Sin2β at BaBar

Stefan Spanier
SLAC

Stanford
Linear
Accelerator
Center

A national laboratory funded by the Department of Energy

Outline

- Another sin2β
- B Factory and BaBar
- Event Selection
- sin 2β Measurement
- Summary / Outlook

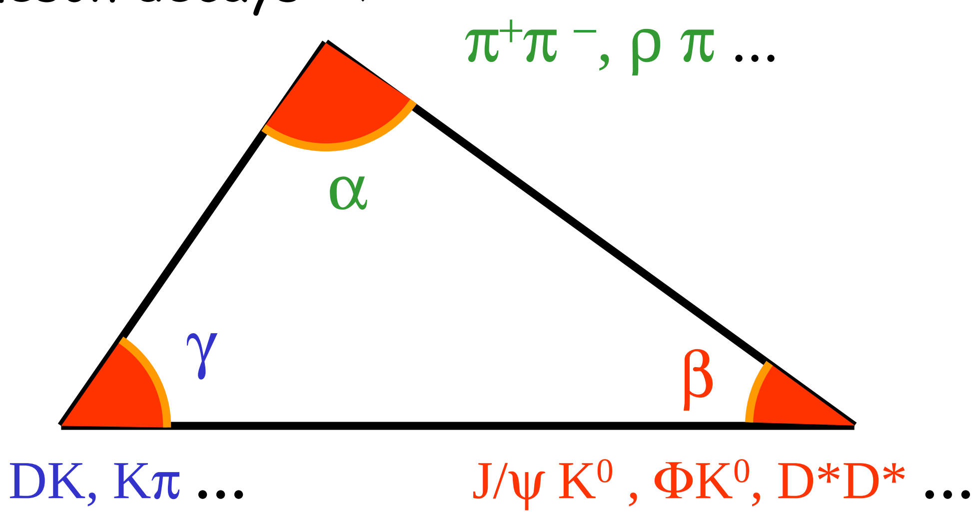
CP Violation in the Standard Model

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

γ

β

B meson decays →



3 strengths,

1 CP phase in V_{td} and V_{ub}

$\alpha = \pi - \beta - \gamma$

Branching Fractions < 10^{-4}

- Magnitude of CP violation $\propto$ triangle area

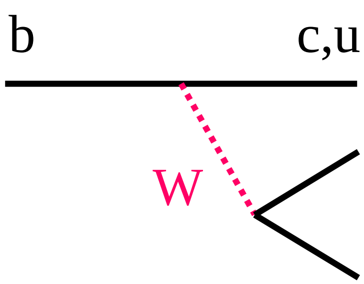
CP Violation in B Decays

CP observation needs interference between at least two different amplitudes:

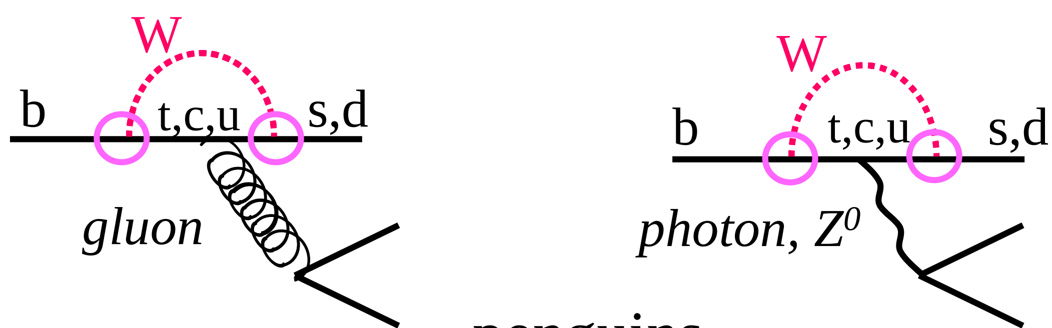
$$A = a_1 \cdot e^{i\phi_1} + a_2 \cdot e^{i\phi_2}$$

… to project out phase by interference.

Decay: for example

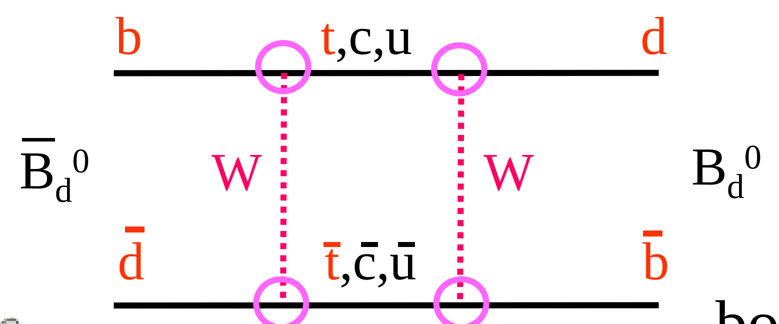


tree



penguins

Mixing:



box

(CP violation in mixing negligible in SM)

New Particles enter:

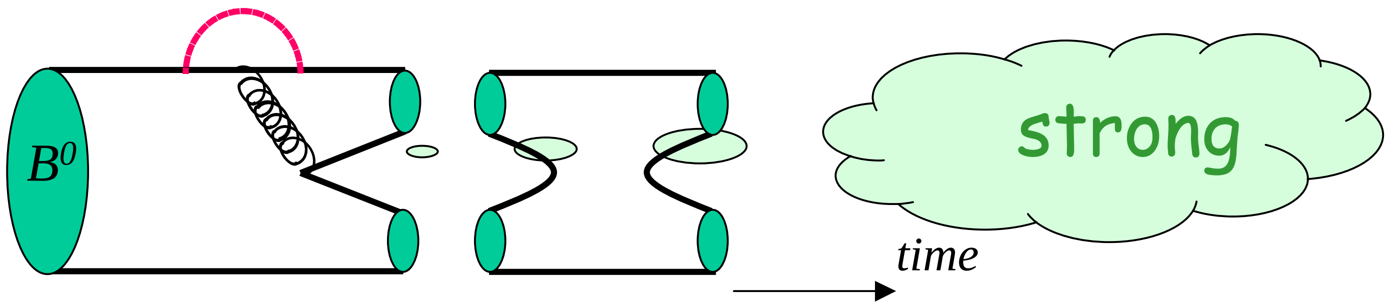
- **new phases**

  (e.g. in MSSM: minimal flavor violation)

  $\Rightarrow$ modification in decay / mixing
- **~ 1 TeV scale**

Direct CP Violation (in Decay)

• CP violation $\Leftrightarrow$ $\text{Rate}(B^0 \to f) \neq \overline{\text{Rate}}(\overline{B}^0 \to \overline{f})$

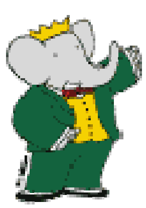


Rate difference:

$$R - \overline{R} = -2 \sum_{i,j} a_i a_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j)$$

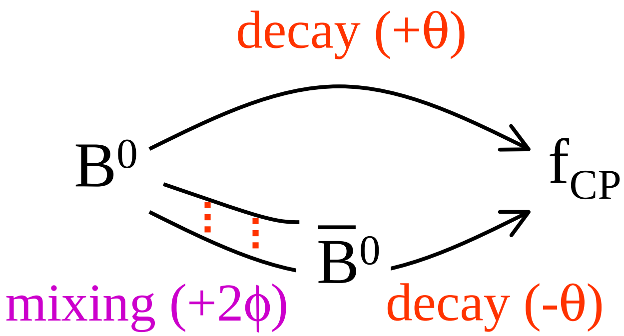
ϕ_i : weak phases δ_i : strong phases

- Many SM % New Physics predictions for RATES, ASYMMETRIES.
- Short range, long range (rescattering) hadronic interactions need to be modeled $\Rightarrow$ B decays are inputs for model builders.



CP Violation in Interference between Mixing and Decay

- $B^0, \overline{B}^0$ decay into same CP eigenstate f_{CP} e.g. $J/\psi\ K^0_S$: CP = -1



- CP violation ⇔ $R(B^0 \to f_{CP}) \neq \overline{R}(\overline{B}^0 \to f_{CP})$

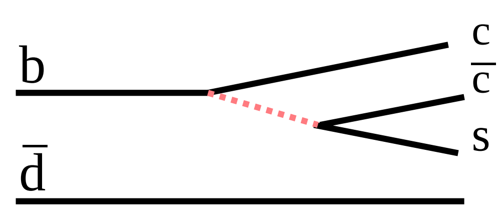
$$\boxed{a(t) = \frac{R-\overline{R}}{R+\overline{R}}(t) = S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}$$

time dependent measurement

- Only one phase dominant in decay and CP violation in mixing negligible:

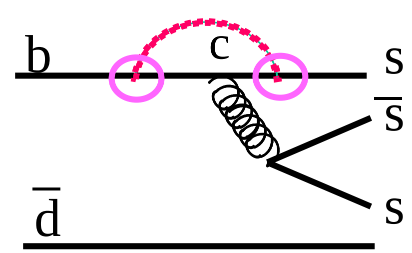
$$\boxed{C = 0,\ S = (CP)\sin 2(\phi + \theta)}$$

$f_{CP} = J/\psi\ K^0_S$ $(b \to c\bar{c}s)$: $S = -\sin 2\beta$



$\theta = 0$

$f_{CP} = \phi\ K^0_S$ $(b \to s\bar{s}s)$: $S = -\sin 2\beta$



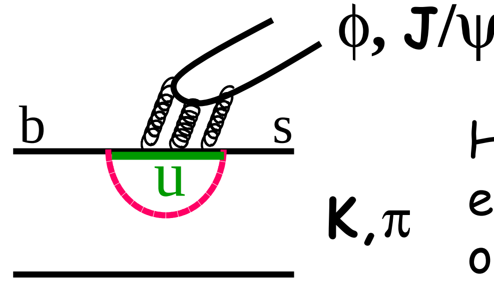
$\theta = 0$ in SM

New Physics : $\Delta a = |\ a_{J/\psi}(t) - a_{\phi}(t)\ |$

Stefan Spanier

How clean ?

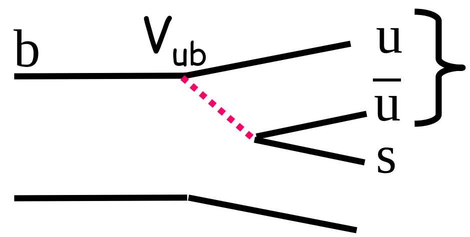
- CKM: subleading penguin have same phase up to $O(\lambda^2)$



How strong is the effective suppression of u-quark loop diagram (A^c > A^u) penguin mode ?

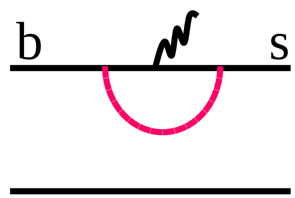
- Flavor SU(3):

  $|\phi\rangle = |\bar{s}s\rangle$ with ~1% uncertainty (ideal mixing of vectors)



$|\eta'\rangle = |\{\bar{u}u, \bar{d}d, \bar{s}s\}\rangle$

- Electroweak penguins:



same phase as gluonic penguins; effective suppression (~25% of gluonic penguins)

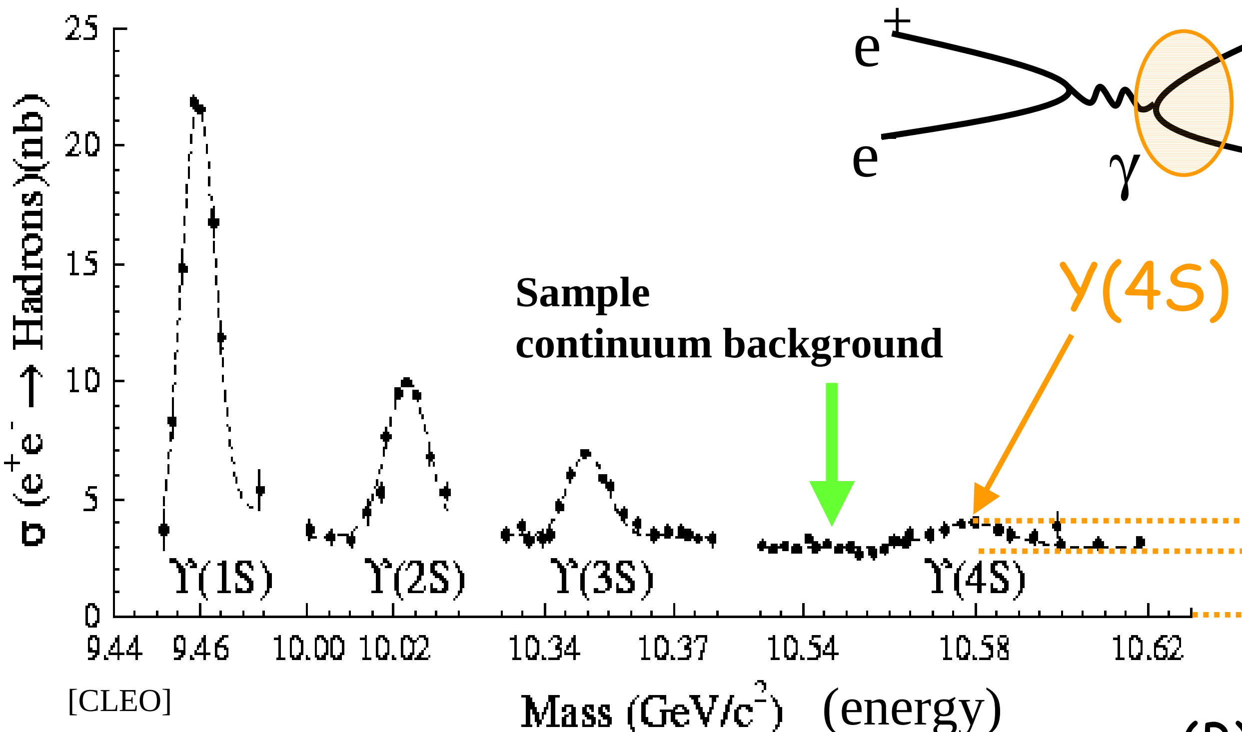
$\Rightarrow$ **in SM:** $\boxed{\Delta a = |\, a_{J/\psi} - a_\phi \,| < 0.04}$

Estimate uncertainty experimentally with flavor SU(3) (b->s % b->d) relating B->ϕK_S to $B^+ \to \phi\pi^+$, $B^+ \to K^*K^+$: $\Delta a < 0.2$ (BF from BaBar, Belle)

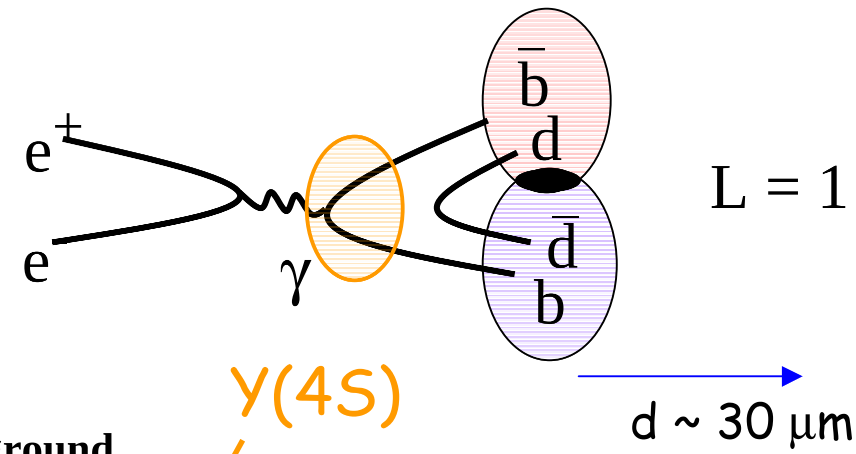
[Grossman, Isidori, Worah]

B-Meson Production

- Electron-Positron collider
  - Υ(4S) resonance decays into B_d-meson pairs (~100%)
  - Can provide high luminosity (rates)
  - Clean environment (~10 tracks/event)
  - Coherent $B^0\bar{B}^0$ production

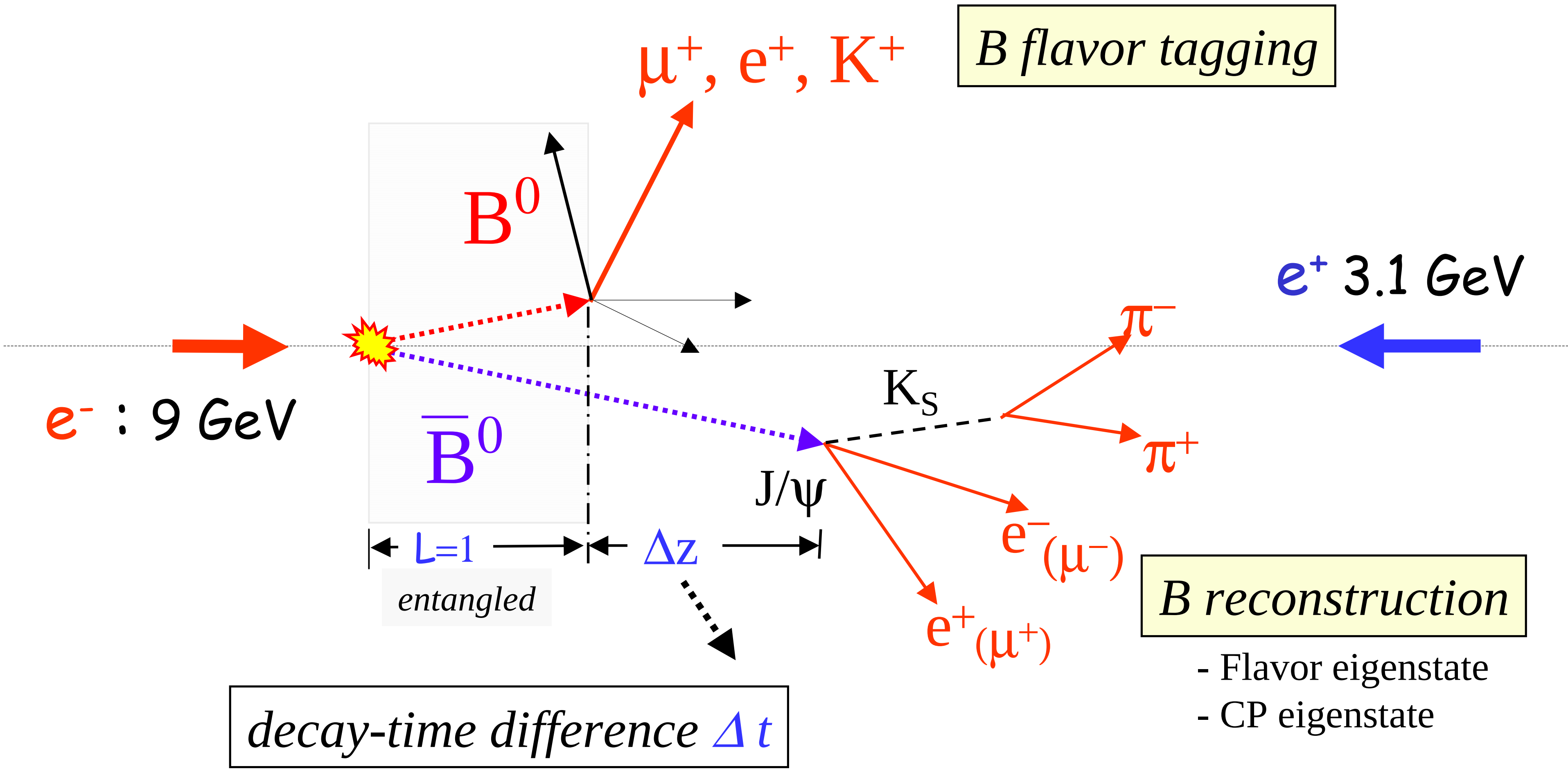


$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadr})} = 0.28$$



mass(B) = 5.279 GeV/c²

Measuring time-dependent B decays

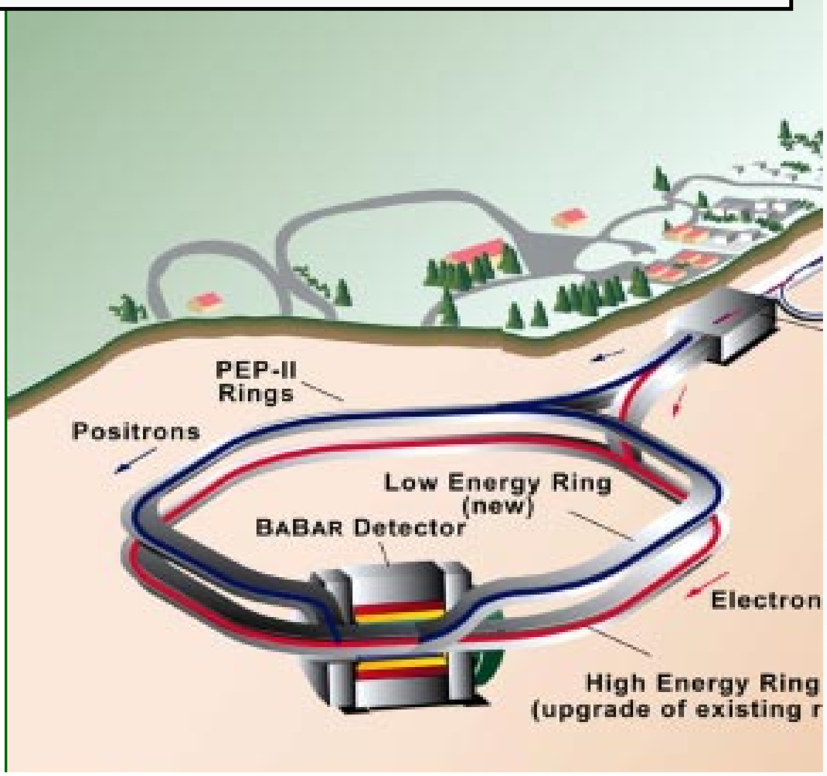


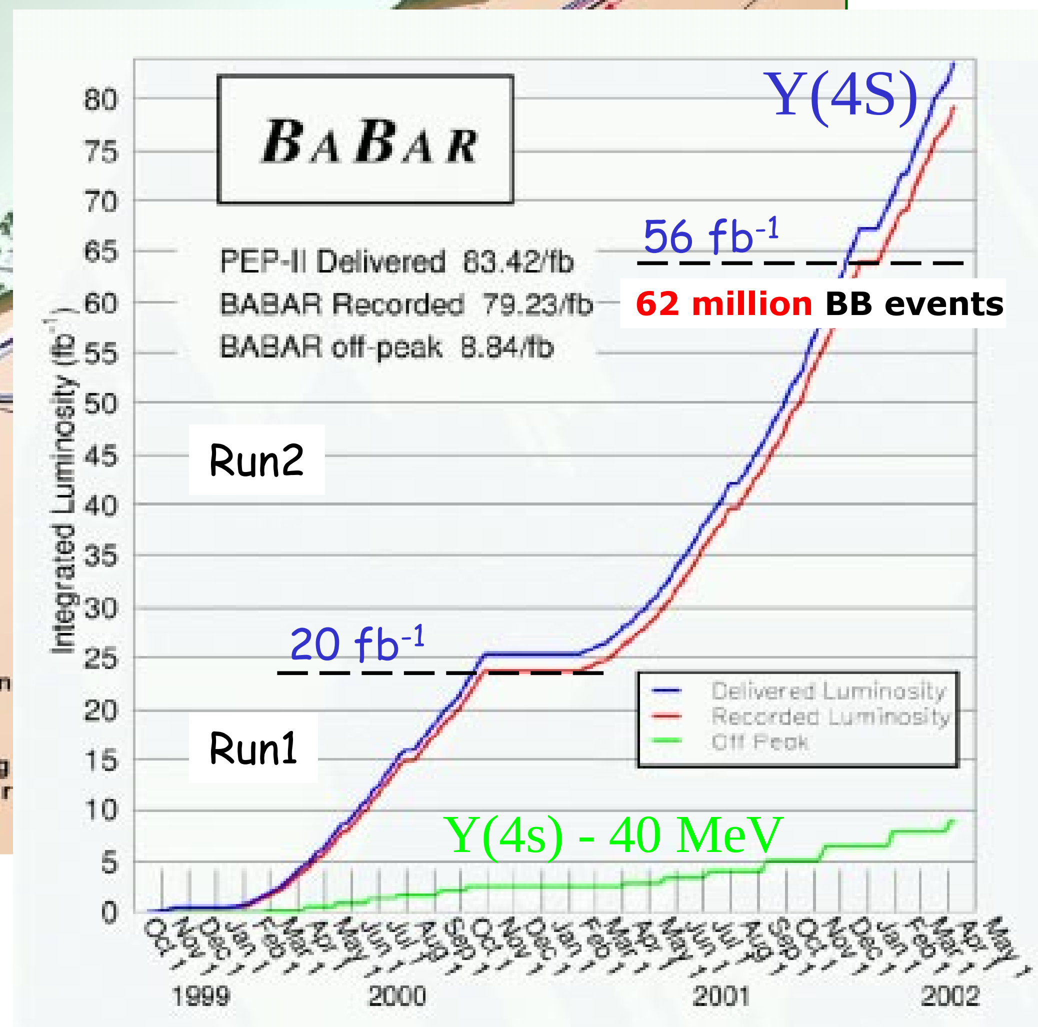
Lorentz Boost $\beta\gamma c\gamma_B \sim 0.55$

$\langle\Delta z\rangle \sim \langle\Delta t\rangle\beta\gamma c\gamma_B \sim 260\ \mu m$

The SLAC PEP-II B factory

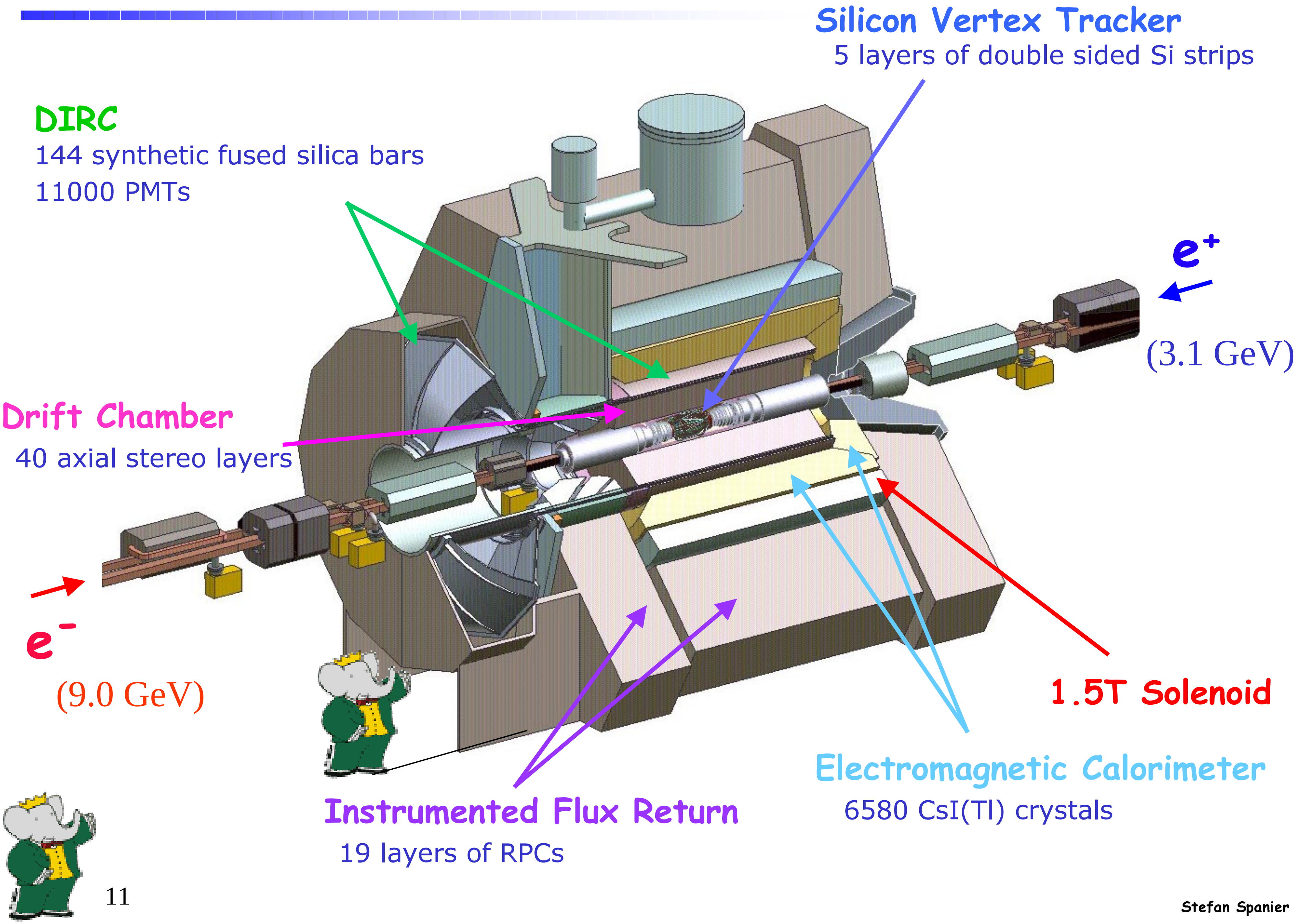
Peak Luminosity :		$< 4.6\ 10^{33}\ /cm^2\ s$
<B- Rate>	:	~ 8 / s
Luminosity/Day	:	303 pb^{-1}





BaBar logging efficiency > 96%

The BaBar Detector



Performance

Tracking

92% of 4π in laboratory SVT + DCH

97% average tracking efficiency

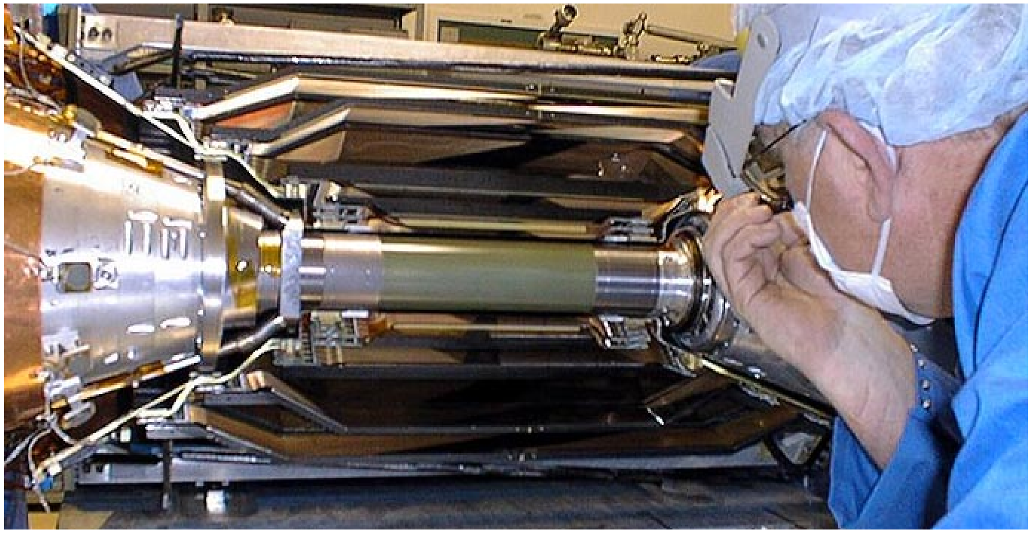
$\sigma(p_T)/p_T \sim 0.5\%$ @ 1 GeV/c

Electromagnetic Calorimeter

$\sigma(E)/E \sim 3\%$ @ 1 GeV

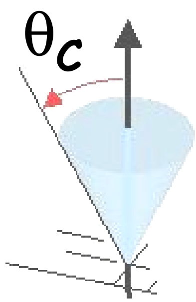
~7 MeV/c^2 π^0 resolution,

for $E_\gamma > 30$ MeV



- SVT Located in high radiation area (inner radius: 3.2 cm)
  - Radiation hard readout electronics (2Mrad)
- Up to 98% hit reconstruction efficiency
- Hit z-resolution ~15 μm at 0^0

Principle of the DIRC



$$\cos\theta_c = 1 / n(\lambda)\,\beta$$

mass (p, θ_c)

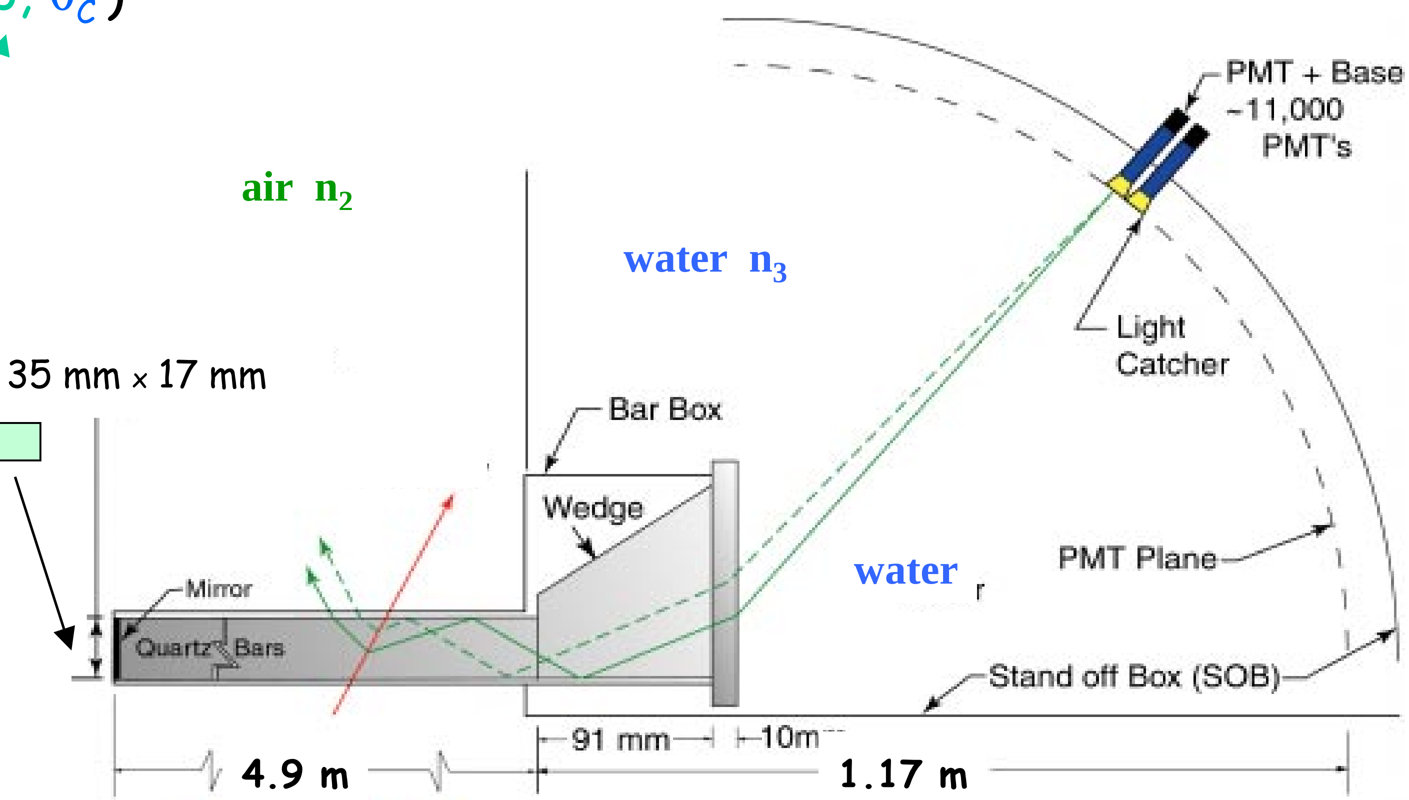
tracking

Pinhole focus

θ_c : Cherenkov angle
n : refraction index
$\beta = v/c$

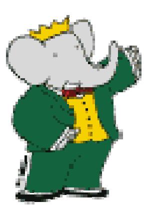
35 mm × 17 mm

4 synthetic fused silica bars glued together



Typical DIRC photon: $\lambda \approx 400$ nm, ~ 200 bounces, ~ 5 m path in quartz.

Geometrical uncertainty $\sigma(\theta_c) = 7.3$ mr



Principle of the DIRC

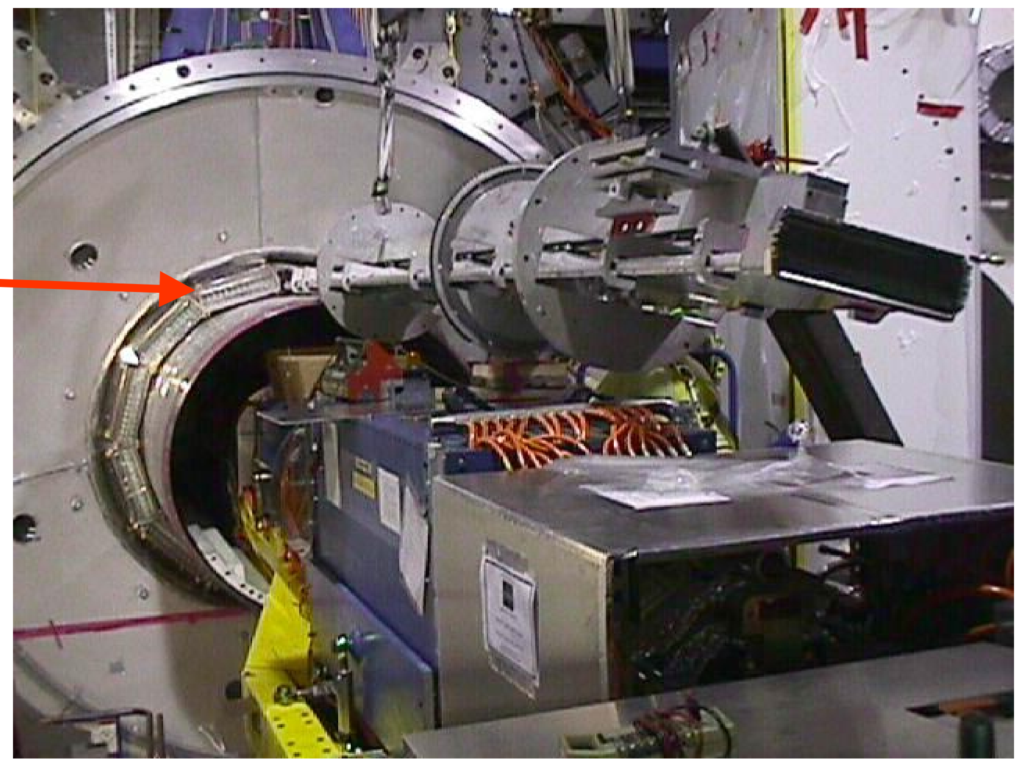
- **12 DIRC sectors**
- **each has one aluminium box with 12 quartz bars kept in nitrogen atmosphere**
- **<u>Coverage</u>:**

87% C.M. polar angle,

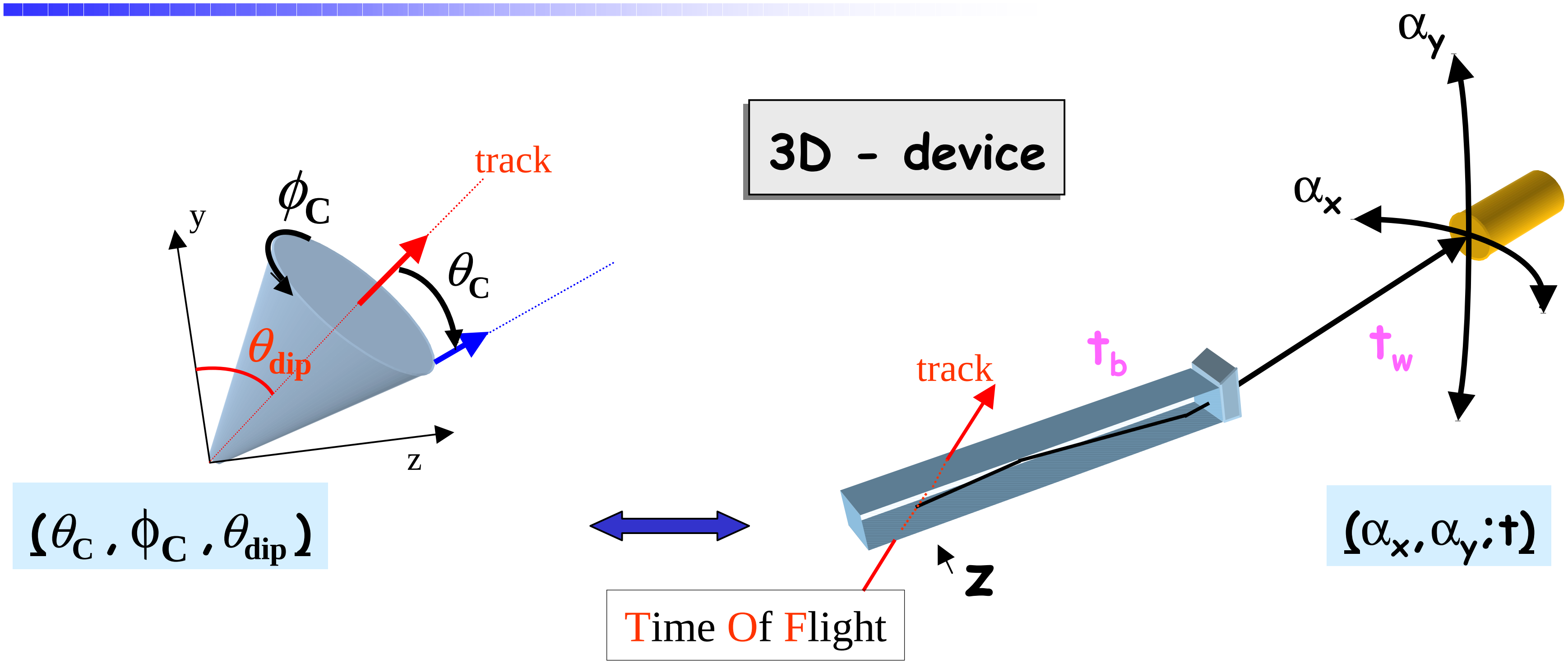
94% azimuthal angle

97% photon production efficiency

Installation of the last bar box



Reconstruction



$$\text{Photon path L in bar} = \frac{z}{\cos(\alpha_x, \alpha_y)} = \frac{\text{coordinate along bar}}{\text{photon direction in bar}}$$

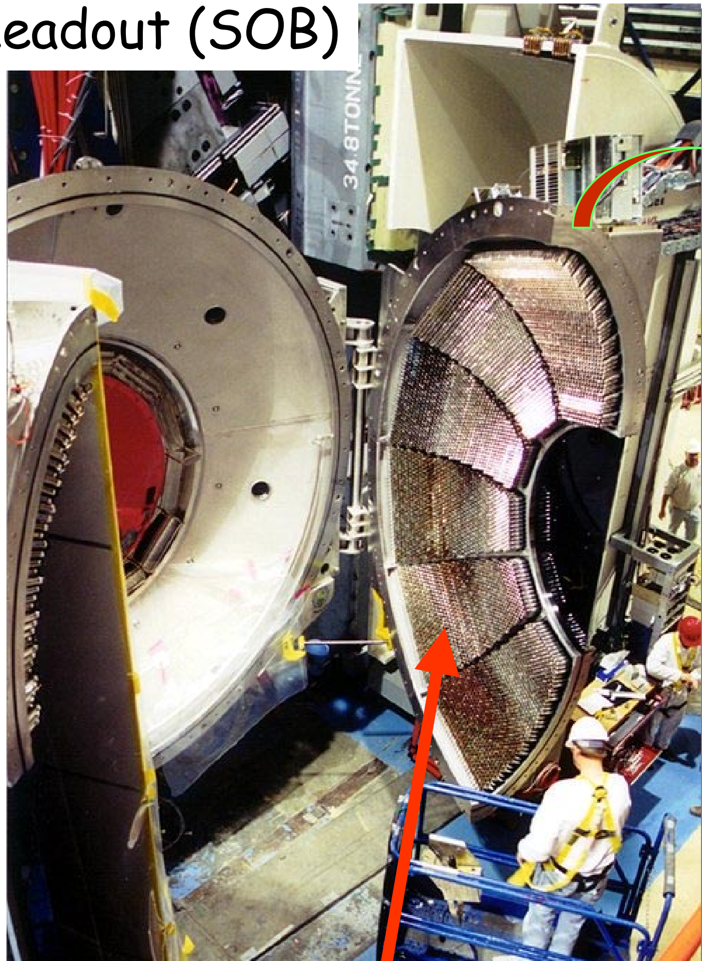
Precise timing t_{DIRC} from reconstruction of the photon path:

bar propagation time $t_b = Length/v = t(\alpha_x, \alpha_y) \sim t(\theta_C, \phi_C)$

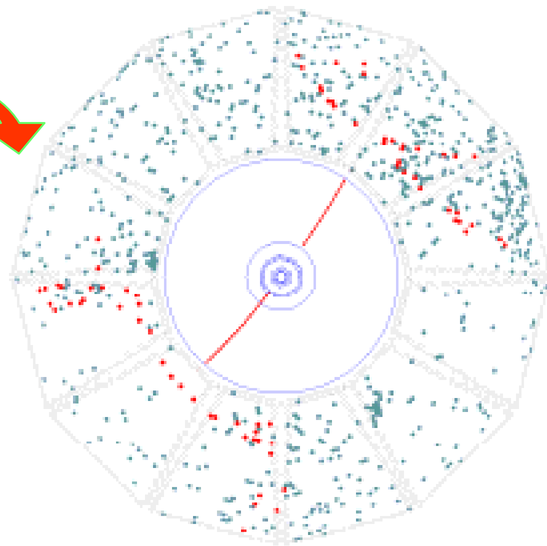
Stefan Spanier

Time Reconstruction

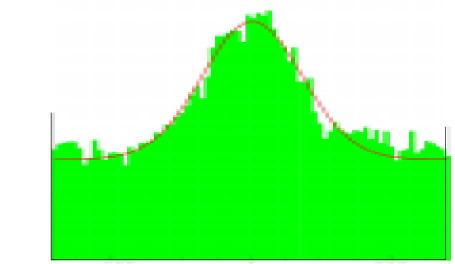
Readout (SOB)



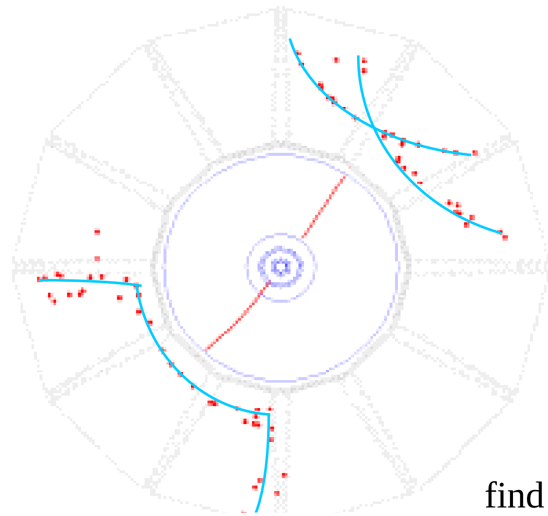
(1) Δt = **raw PMT hit time – L_1 trigger time**



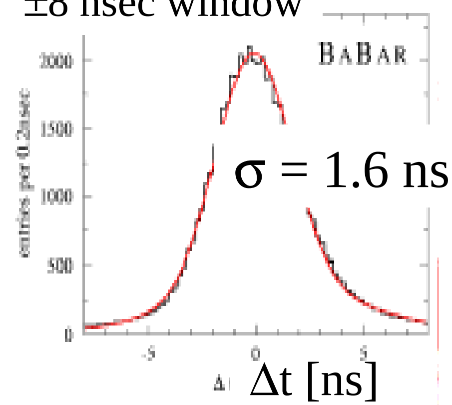
$\pm$300 nsec L_1 trigger Window ($\sigma \sim$ 65 ns)



(2) Δt = t_{DIRC} - **track time (TOF)** - < t_{PMT} >



$\pm$8 nsec window

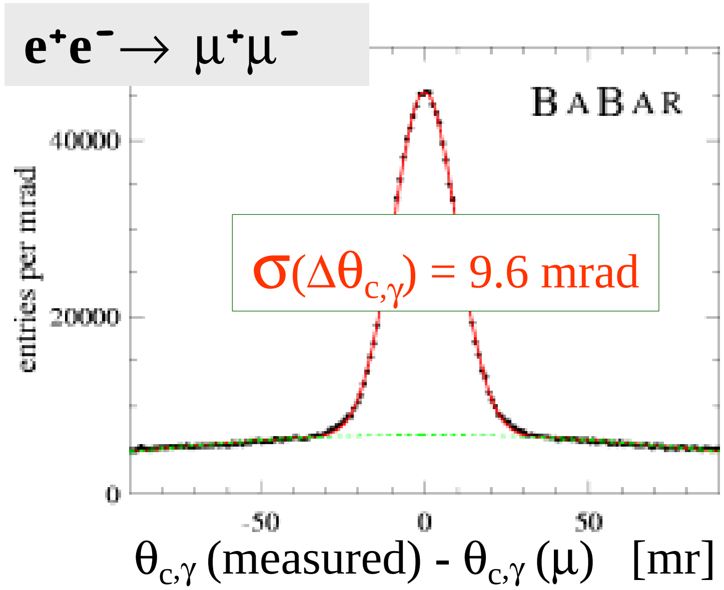


find colliding bunches

1 beam-background hit/sector/event

Angle Reconstruction

- Single Photon Angle Resolution



resolution dominated by:

7.3 mrad from PMT/bar size,

5.4 mrad from chromatic term,

~2 mrad from bar imperfections.

~10% background under $\Delta\theta_{c,\gamma}$ peak:

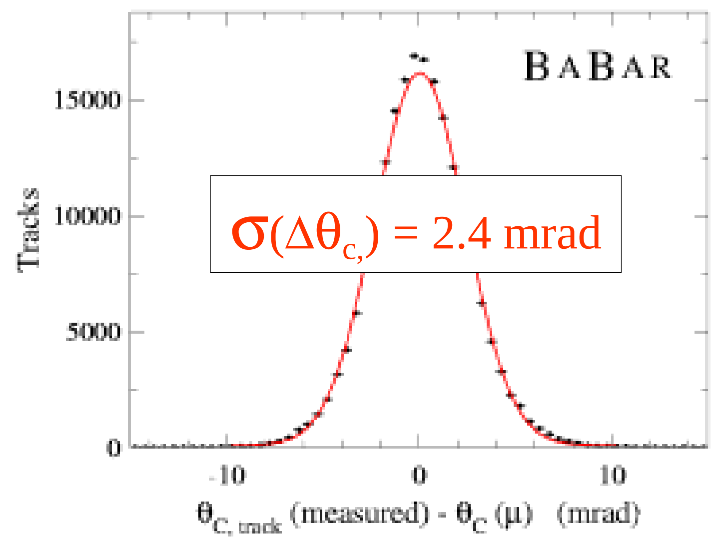
(scintillation, PeP II background negligible)

- Track Cherenkov angle resolution

$$\boxed{\sigma_\theta = \sqrt{\sigma_{track}^2 + \sigma_{\theta\gamma}^2 / N_\gamma}}$$

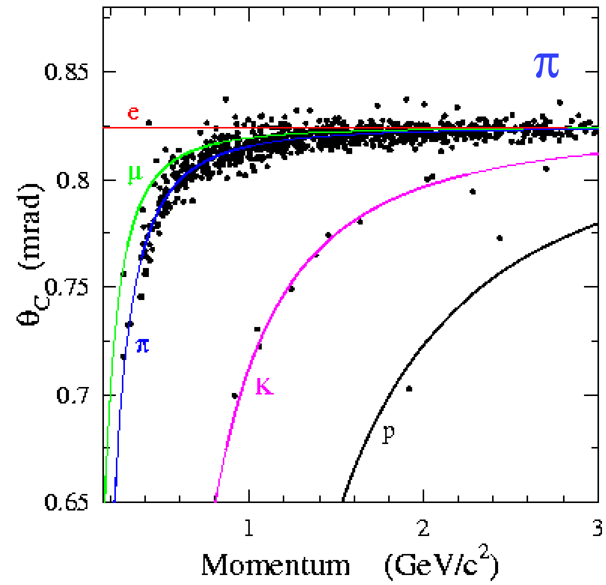
here $N_\gamma \geq 28$

.. is within ~10% of design.



Kaon Identification

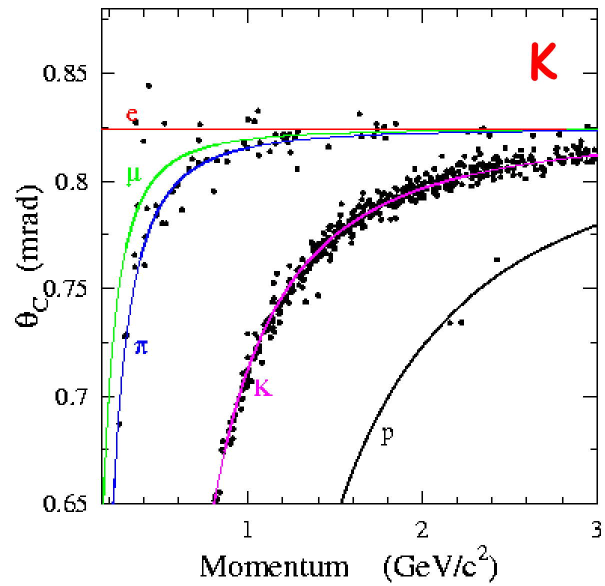
- For selection combine the Gaussian $G(\theta,\theta_C)$ with Poissonian $P(N_\gamma, N_{expected} + N_{bck})$ of photon counting (and drift-chamber and SVT dE/dX (Gaussian))



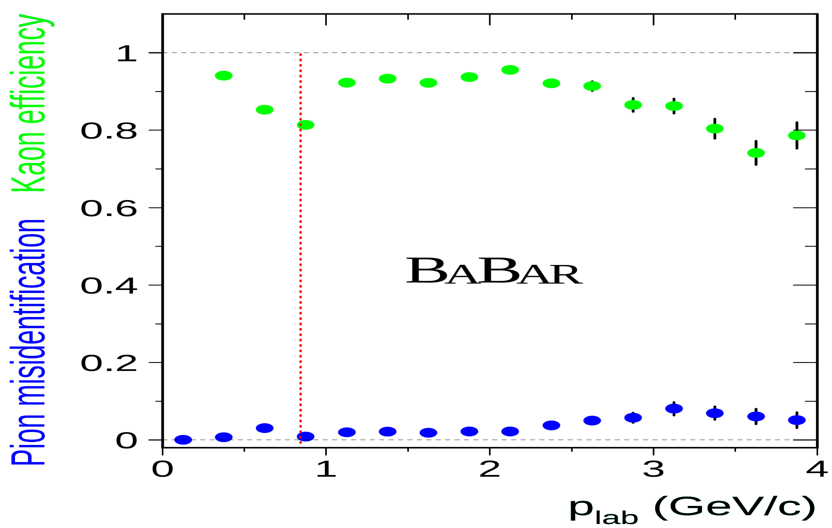
- Tuning using control channels, e.g.

$$D^{*-} \rightarrow D^0 \pi^-$$
$$\hookrightarrow K^- \pi^+$$

identify the π and K from the D^0 kinematically.
Correct for combinatorial background (~10%).



SVT + DCH + DIRC



Future

- Better time resolution

1) At about 200ps the time information becomes competitive with the spatial resolution
2) Sensitivity to chromatic smearing via dispersion:

$$\Delta t : t_{calculated} = L\ (\ \cos\Theta_C = 1/n_{phase}(\lambda)\ \beta\ )/v$$

$$- \ t_{measured} = L/v_{group} \qquad v_{group} = c/n_{group}$$

$\Rightarrow$ ~ 1 ns shift for typical photon

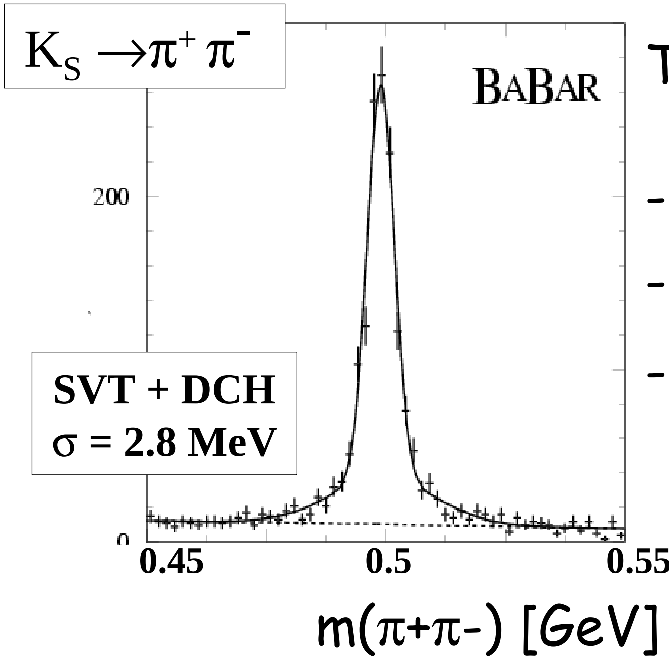
- Large water tank collects background

Low energy photons, energy E < 2-2.5 MeV (for 90% of them), from accelerator make Compton scattering in water/quartz;
Radiative Bhabha hit area below SOB

$\Rightarrow$ Compactify readout plane and improve time resolution

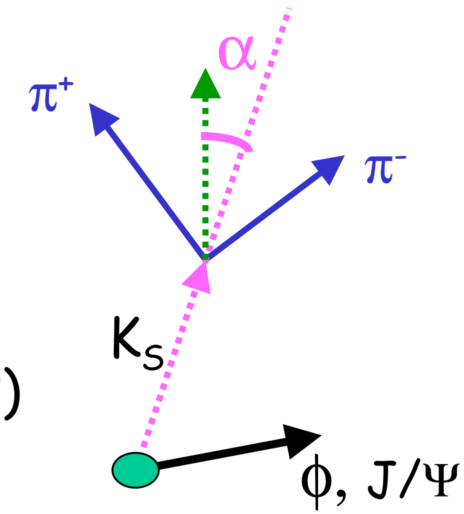
e.g. modified optics (focusing) and flat panel multi-anode PMTs

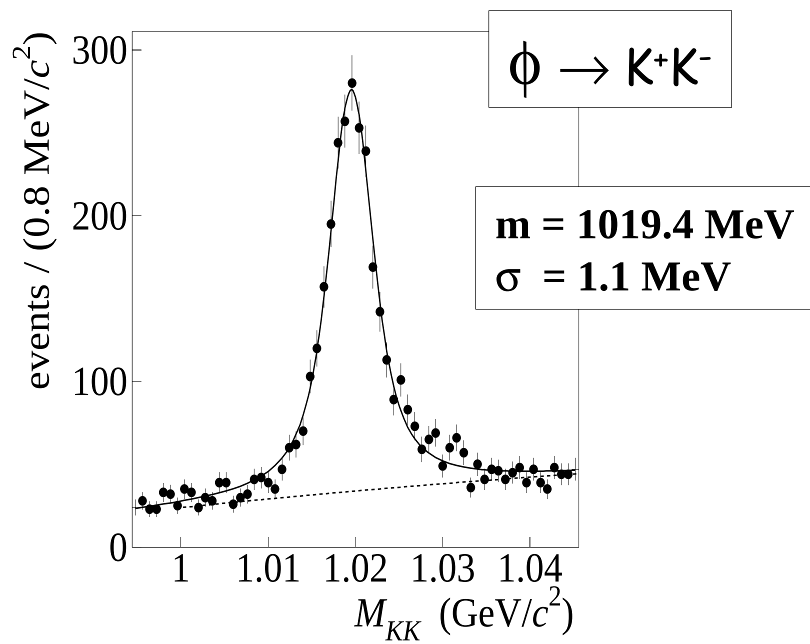
Resonances

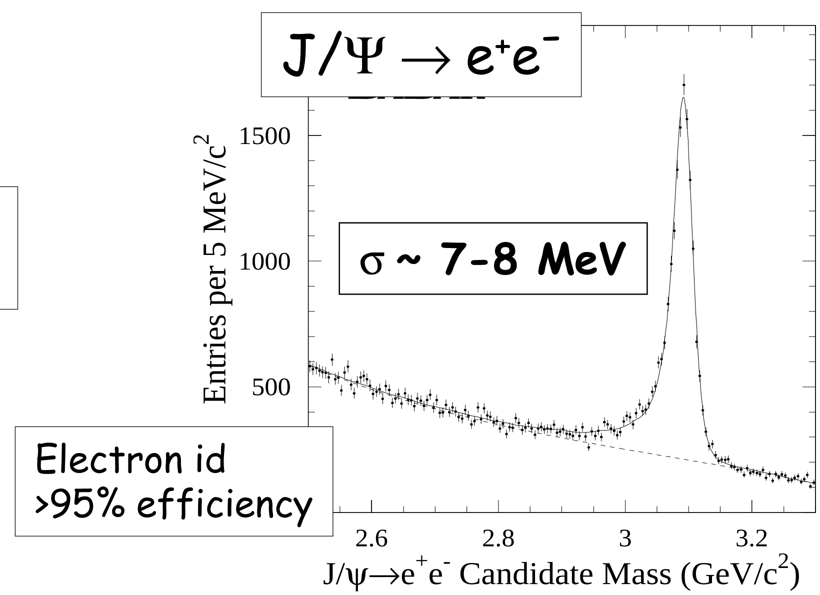


Typical K_S selection:

- mass cut
- cos α
- lifetime significance τ/σ(τ)







B^0 Reconstruction

Energy & Momentum conservation:

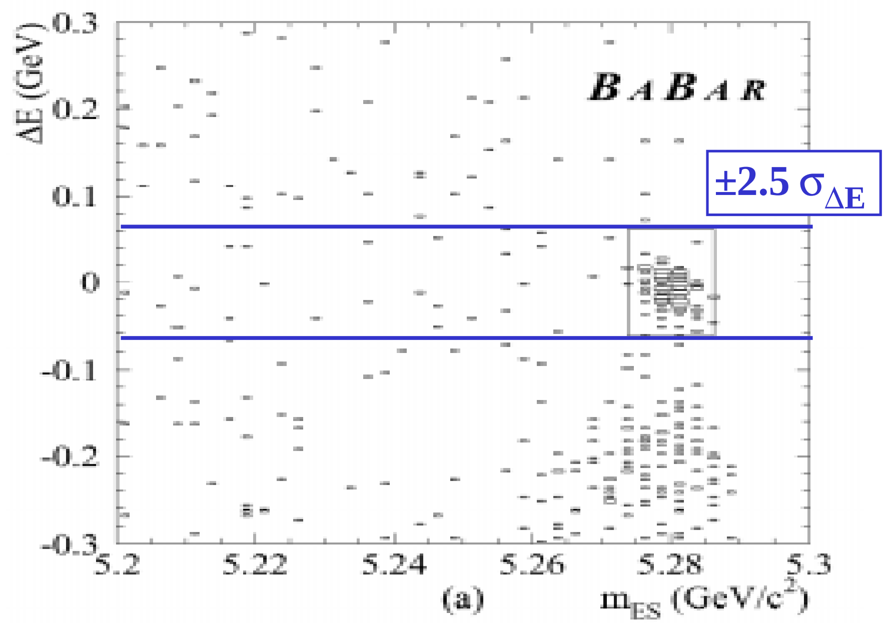
Energy Difference in CoM

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

Beam Energy-Substituted Mass

$$m_B = m_{ES} = \sqrt{E_{\text{beam}}^{*\,2} - p_B^{*2}}$$

$B^0 \rightarrow D^{*-}\pi^+(K\pi)$



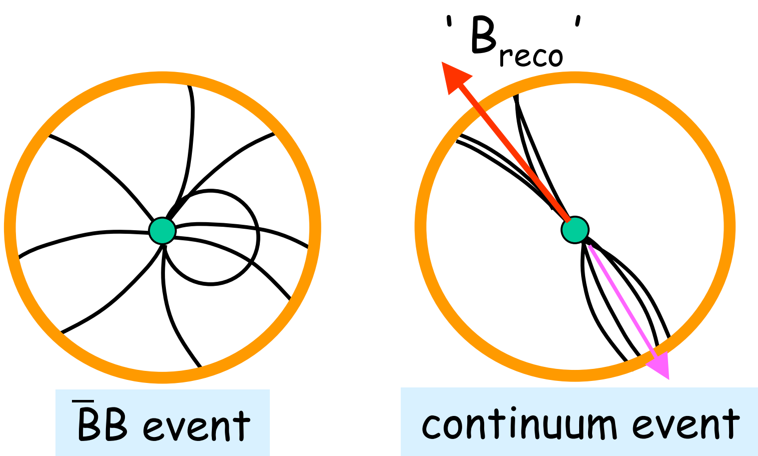
Typical resolutions:

$\sigma(\Delta E)/E_{beam}$	~	15 – 30 MeV	Detector
$\sigma(m_{ES})$	~	2 – 3 MeV	Accelerator

Reconstruction of Rare Decays (charmless)

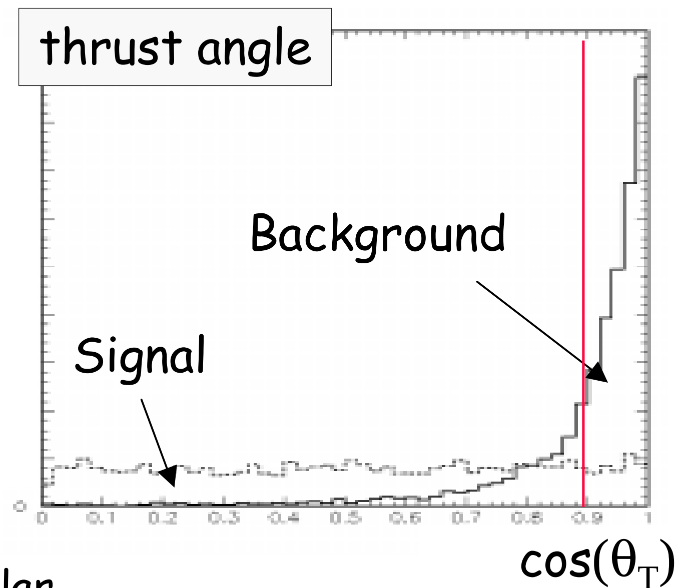
Distinct signatures : -> $\bar{B}B$ background minor
-> continuum background (jet)

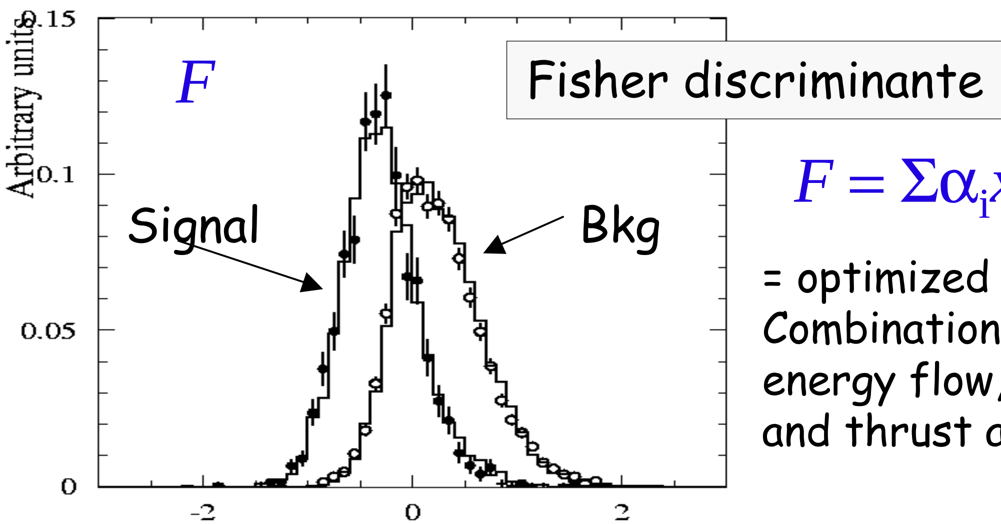
<u>Event topology</u>:



.. use shape variables,e.g. angle between Thrust axis and 'B' direction:

$$\text{Thrust : max } \Sigma|\vec{p}_i \cdot \overrightarrow{\text{thrust}}| / \Sigma|\vec{p}_i|$$





$$F = \Sigma \alpha_i x_i$$

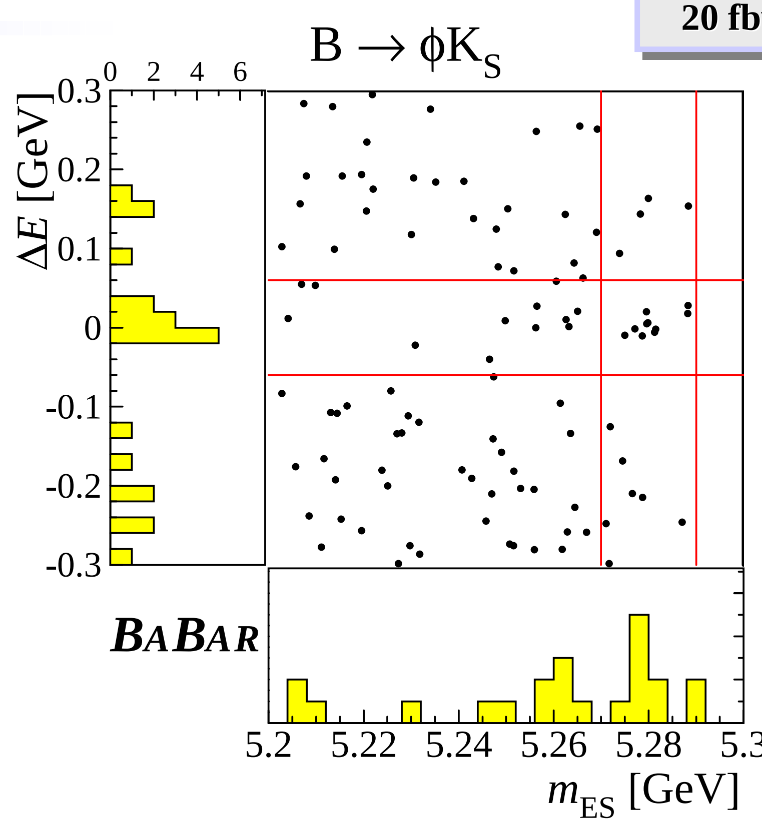
= optimized linear Combination of angular energy flow, B-emission and thrust angle.

Reconstruction of ϕK_S

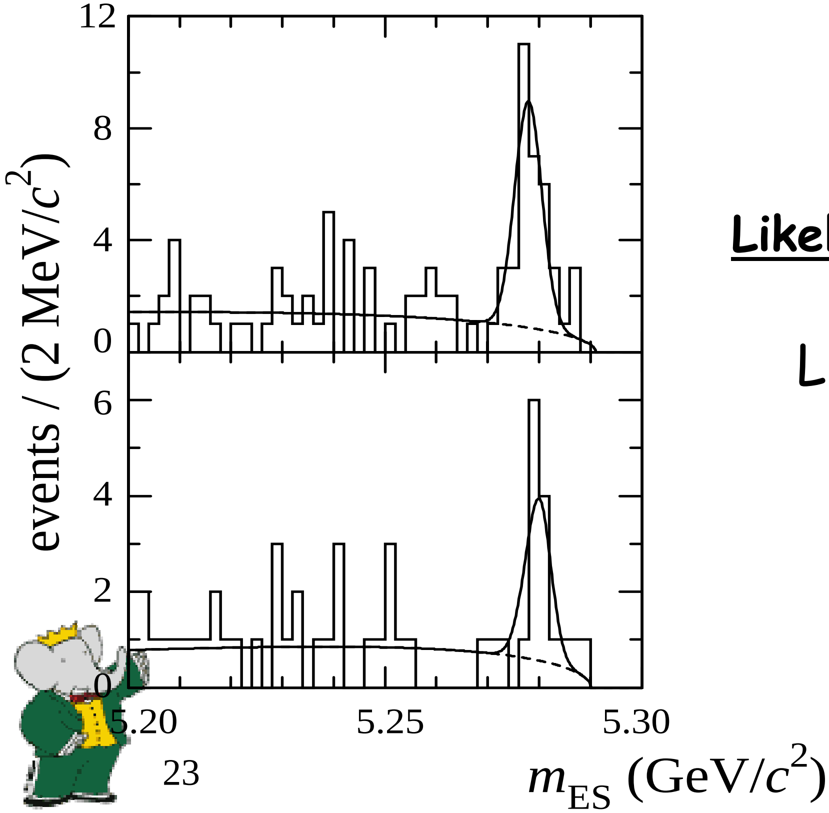
BABAR
20 fb^{-1}

- Published on 20fb^{-1}
- Optimize event selection for

  max$[S^2/(S+B)]$



- Extended unbinned maximum likelihood fit for signal and background (relax cuts):



Likelihood :

$$L = \exp\left(-\sum_i^M n_i\right) \prod_k^N \left(\sum_i^M n_i P_i (x_k,a) \right)$$

Π (Probability density functions)

M categories: Signal, Background
PID K/π

Penguin Modes

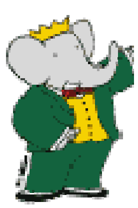
BABAR
20 fb^{-1}

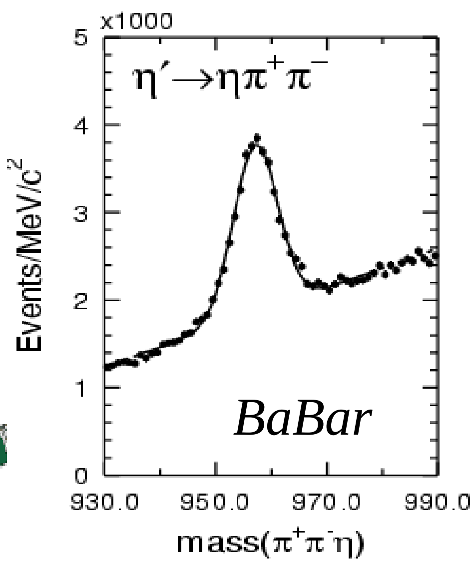
B->ϕK :

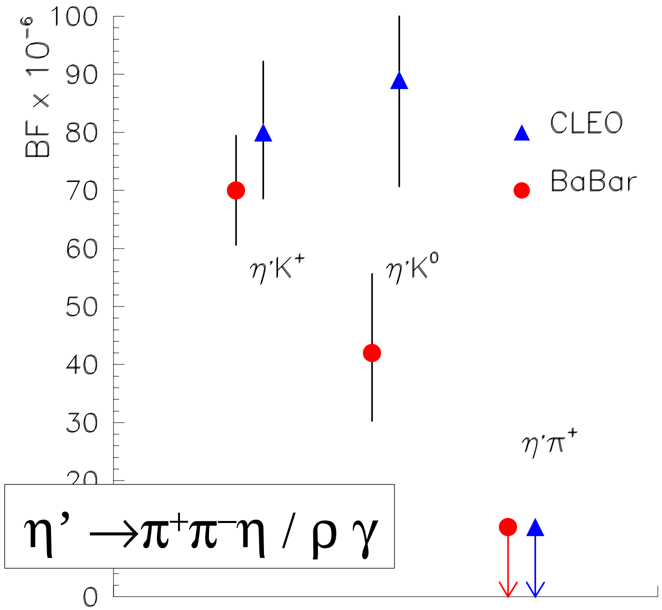
Channel	BF (10^{-6})	signal events	
$B^+ \to \phi K^+$	$7.7^{+1.6}_{-1.4} \pm 0.8$	~ 31	*control channel*
$B^0 \to \phi K^0(K^0_S)$	$8.1^{+3.1}_{-2.5} \pm 0.8$	~ 11	*CP channel*
$B^0 \to \phi K^{*+}(K^+\pi^0, K^0\pi^+)$	$9.7^{+4.2}_{-3.4} \pm 1.7$	~ 11	
$B^0 \to \phi K^{*0}(K^+\pi^-)$	$8.6^{+2.8}_{-3.4} \pm 1.1$	~ 17	
$B^0 \to \phi \pi^+$	< 1.4 (90% C.L.)	~ 1	

... so far only $K^0_S \to \pi^+\pi^-$

B->η'K :







$\eta' \to \pi^+\pi^-\eta$ / $\rho\,\gamma$

	signal events
$B^+ \to \eta' K^+$	~ 137
$B^0 \to \eta' K^0$	~ 27

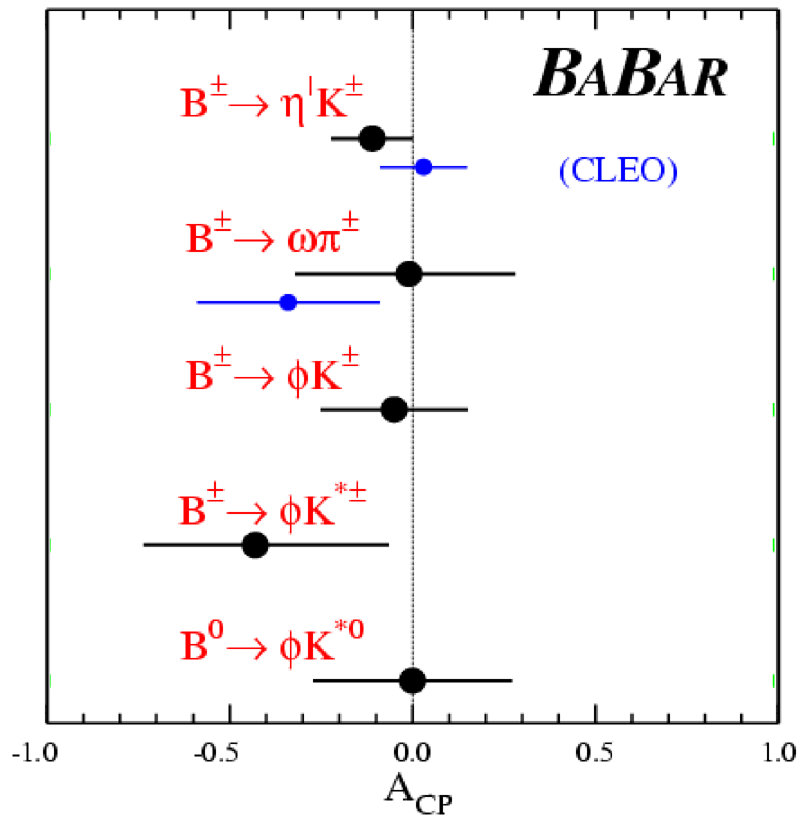
Direct CP Measurements

BABAR
20 fb^{-1}

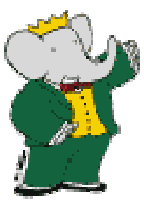
In channels b->u tree + b->s / b->d penguins
sensitive to γ, $\beta+\gamma$,
<u>but</u>: strong phase weakens any quantitative relation to weak phase angles !

Measure charge asymmetry : $A_{CP} = \dfrac{n_i^+ - n_i^-}{n_i^+ + n_i^-}$

Pure penguin $\phi K^{\pm(*)}$: in SM $A_{CP} \sim 0$



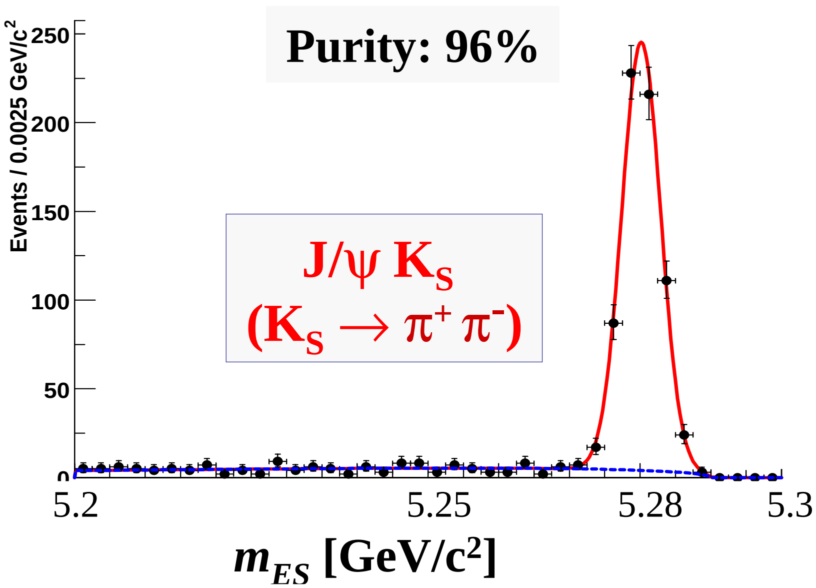
Uncertainty:
1 – 2 % charge asymmetry in PID
2 – 3 % PDF models (6% for K*->Kπ^0)

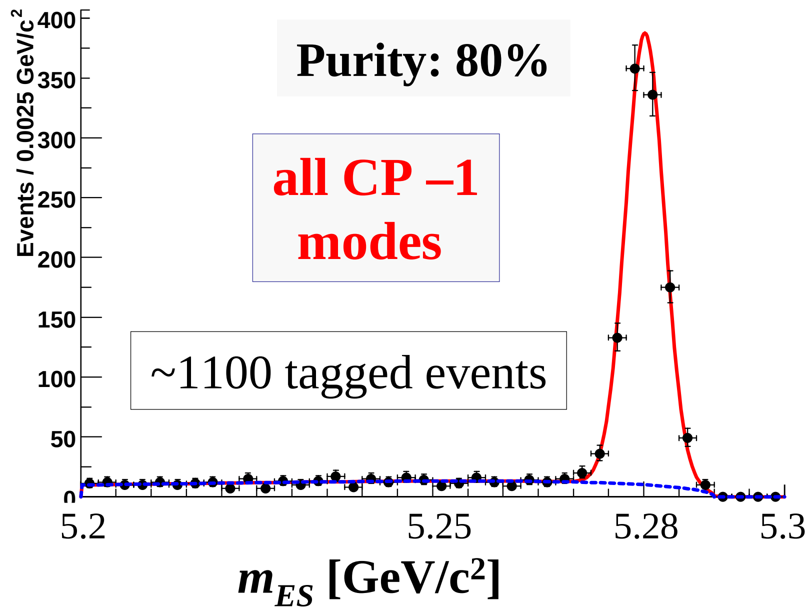


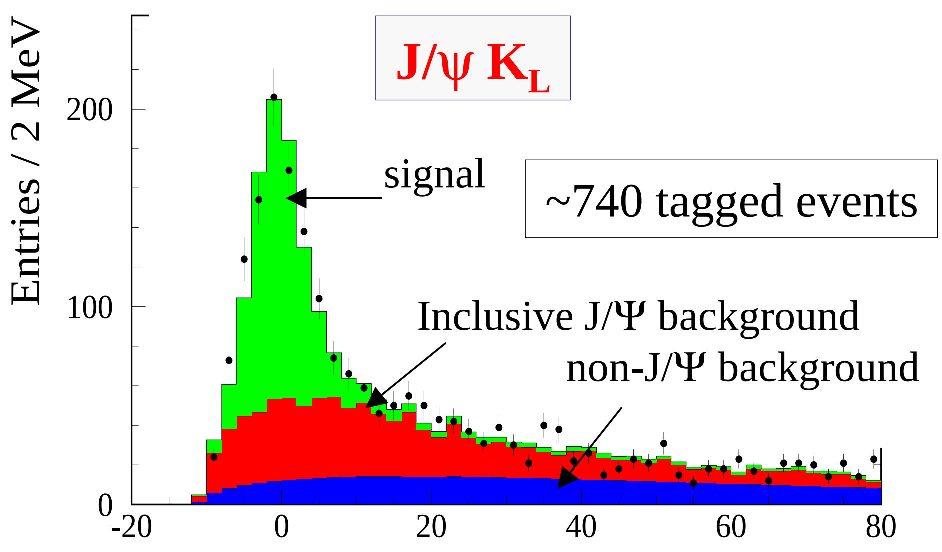
Sin2β Samples (before tagging)

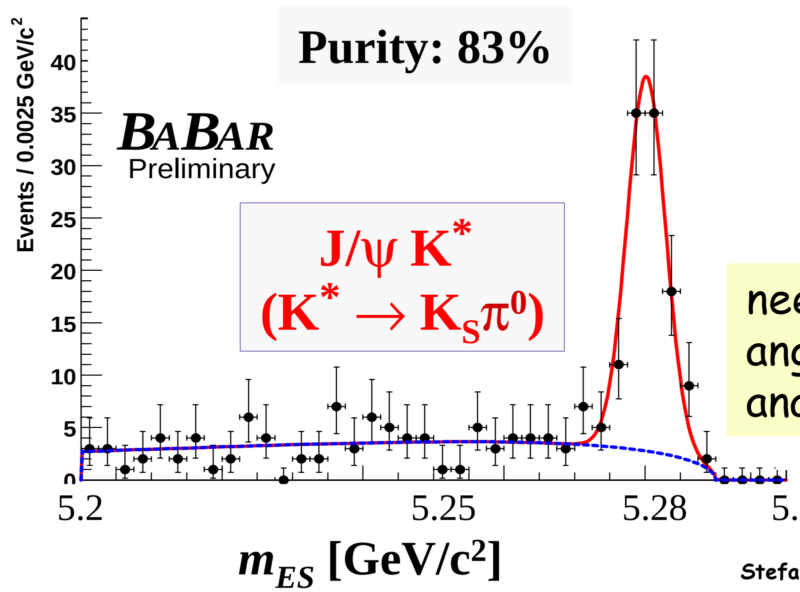
BaBar preliminary

BABAR
$56\ fb^{-1}$









needs angular analysis

Stefan Spanier

Impact of tagging and resolution on CP

perfect tagging + perfect resolution

imperfect tagging + perfect resolution

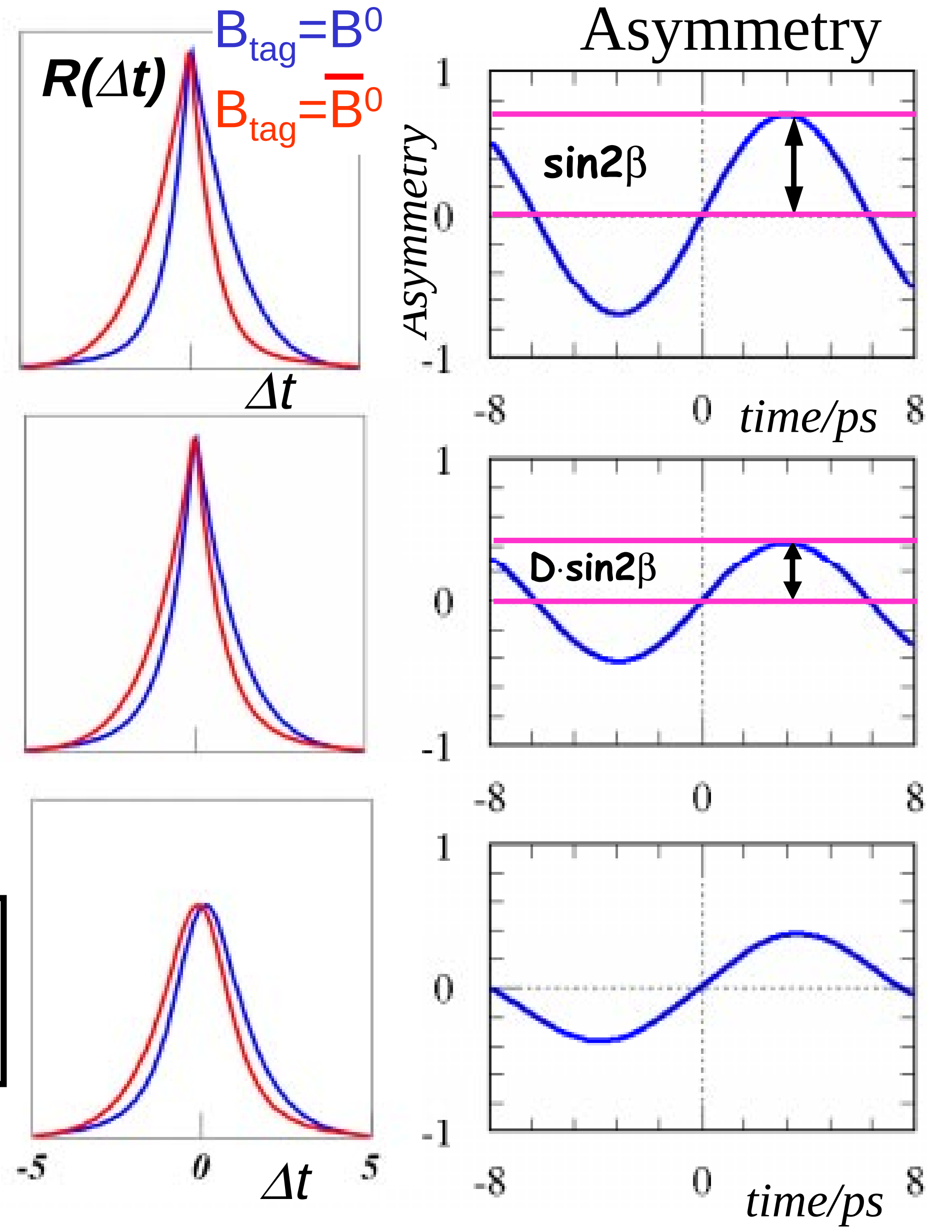
dilution D = (1 - 2 ω)

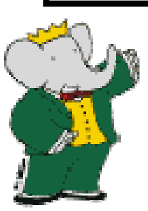
ω : probability of wrong assignment

imperfect tagging + imperfect resolution

$$R(\Delta t) \sim e^{-|\Delta t|/\tau_B}$$
$$(1 \pm \eta_{CP}\, D\, \sin 2\beta \sin \Delta m_d \Delta t\,) \otimes \Sigma(\Delta t)$$

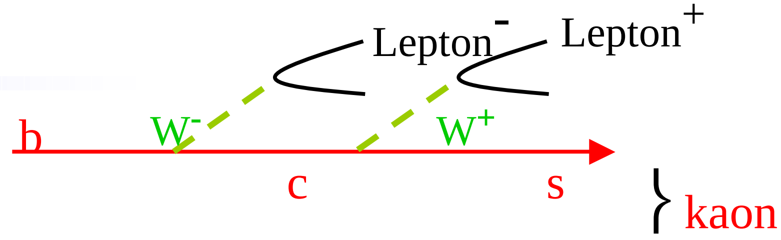
resolution function





Stefan Spanier

Flavor tagging



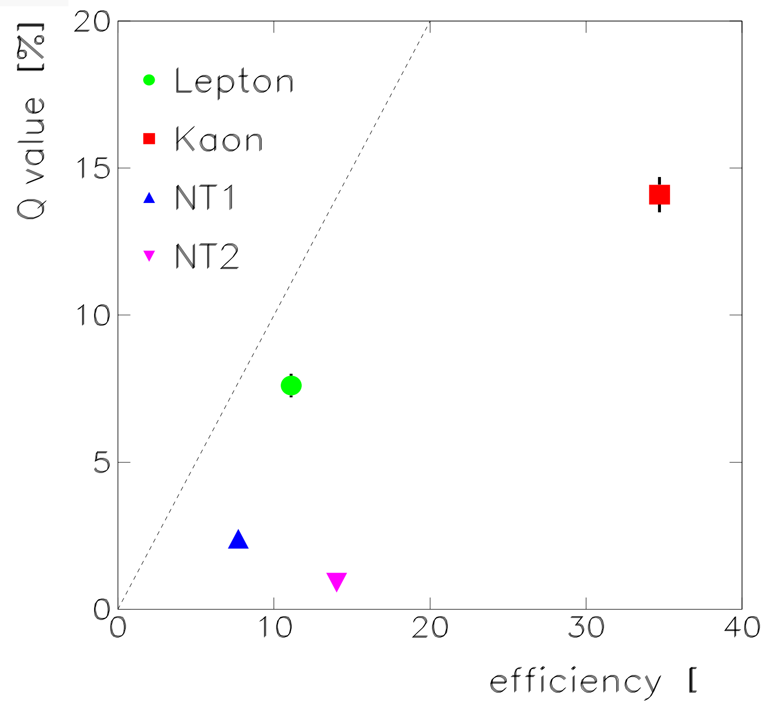
4 categories pre-defined using
- particle identification selectors
- neural-network selection to resolve residual set

ε : efficiency

ω : mistag-fraction $D = (1 - 2\,\omega)$; quality $Q \equiv \varepsilon D^2$

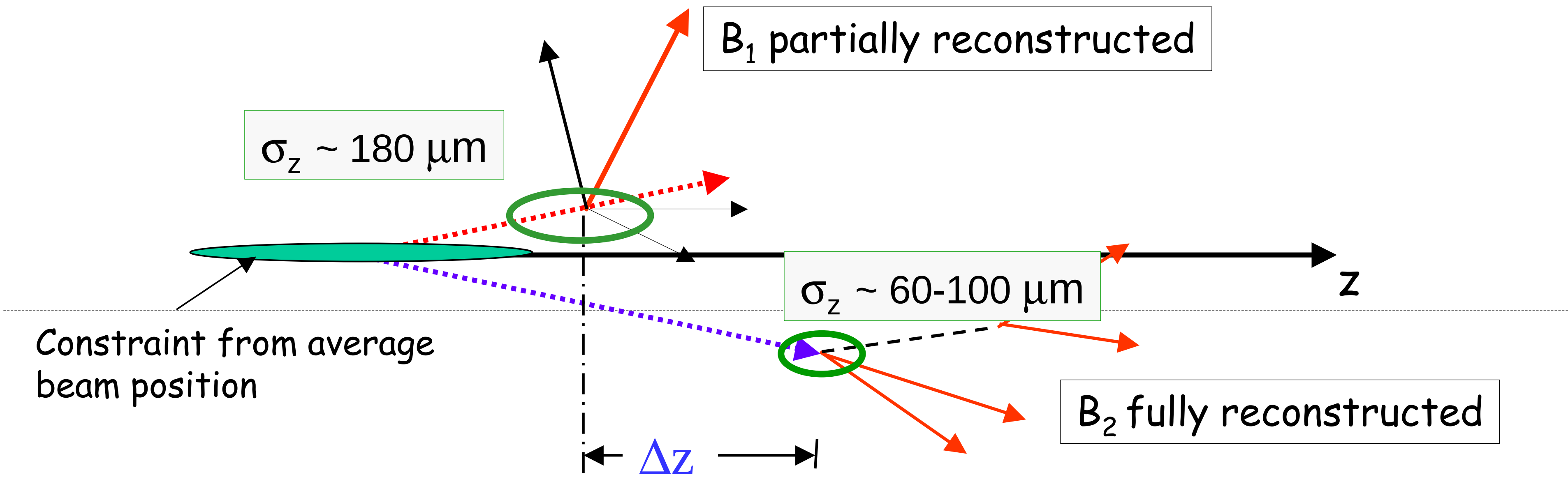
- precision $\sigma(\sin 2\beta) \sim 1 / \sqrt{Q N}$

<u>**Mis-tagging probabilities**</u>
<u>from the data</u>, using the sample of fully reconstructed *B* decays.



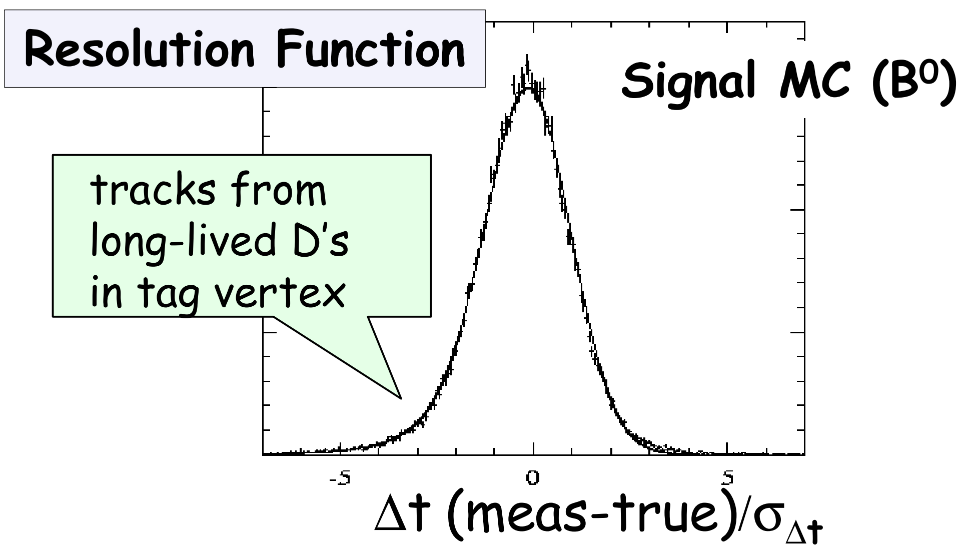
$Q_{total} = (25.1 \pm 0.8)\%$

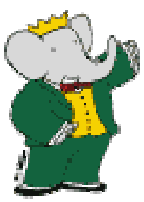
Vertexing



- Efficiency ~ 97% (1-prongs included)
- Resolution dominated by tag-side
- Average Δt resolution ~ 0.6 ps

Δt resolution function (3 Gaussian) modeled on Monte Carlo, measured from the B-flavor sample

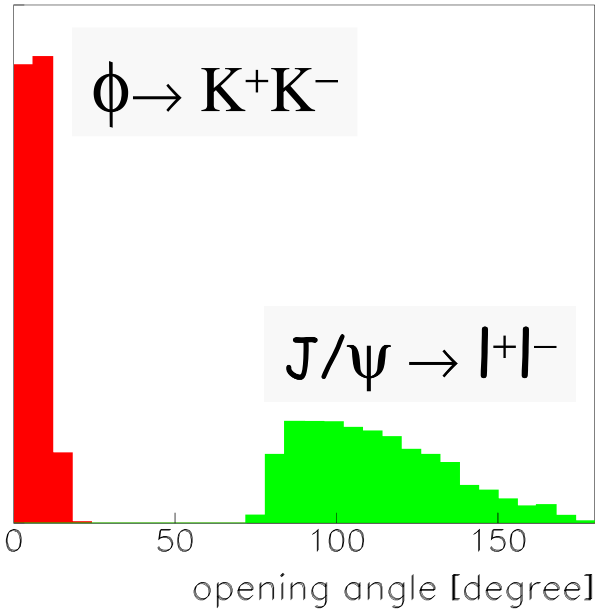




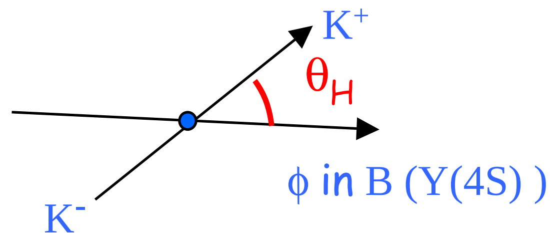
Stefan Spanier

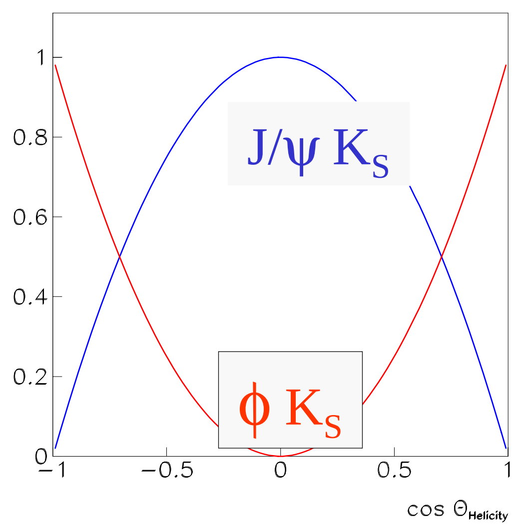
Vertexing (ΦK % J/Ψ K)

Opening angles quite different:

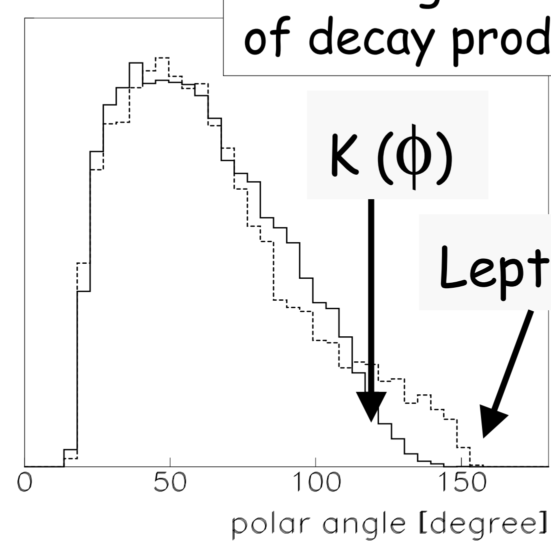


B->ϕ K : - large Q-value
- helicity angle ~ $\cos^2\theta$





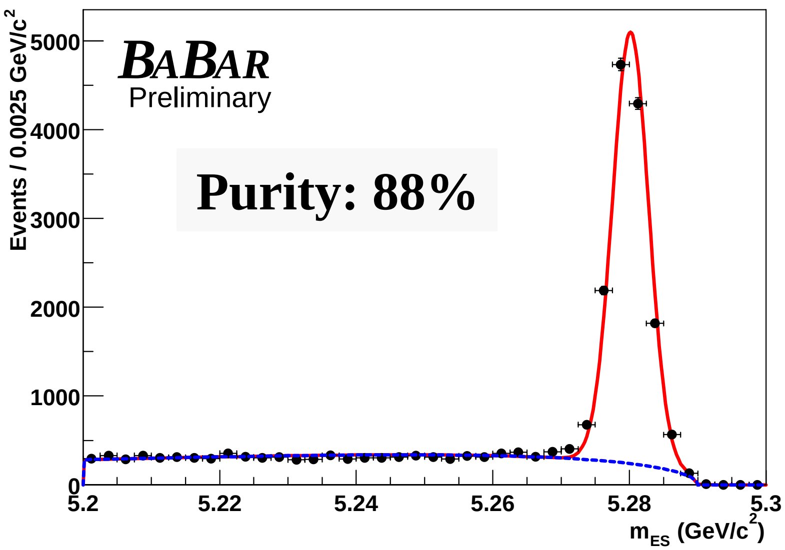
Polar angle distribution of decay products



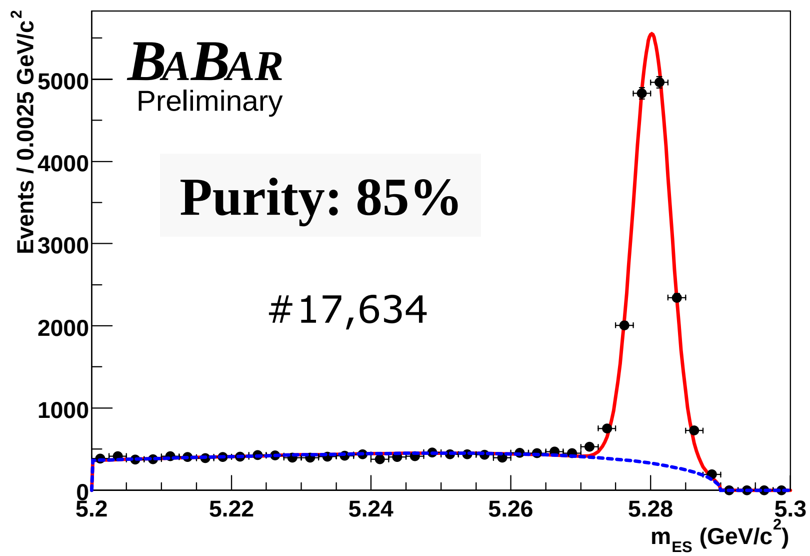
Stefan Spanier

Flavor Sample

$B^+ \to \bar{D}^{(*)0}\,\pi^+,\ J/\psi\, K^+, ..$



$B^0 \to D^{(*)-}\,\pi^+/\rho^+/a_1^+,\ J/\psi\, K^{*0}(K^+\pi^-)$



Proof of principle:

Lifetime :

$\tau_{B^0} = 1.546 \pm 0.032 \pm 0.022$ ps

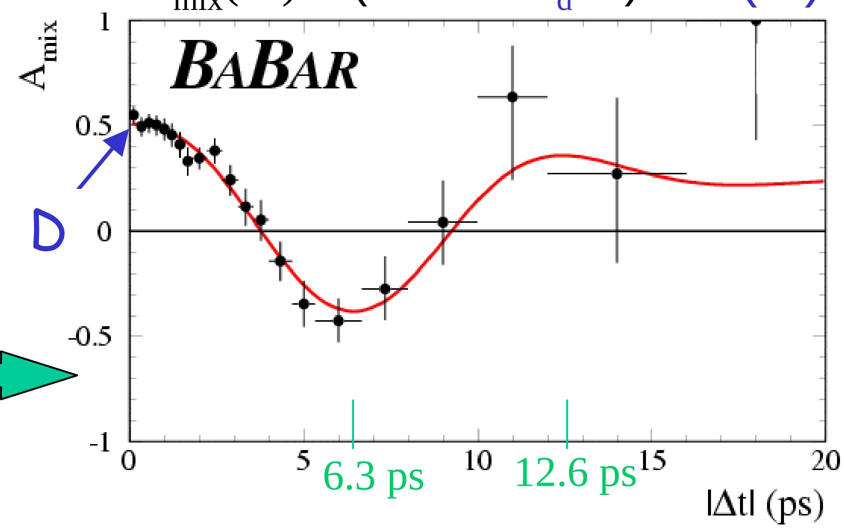
Mixing :

$\Delta m_d = 0.493 \pm 0.012 \pm 0.009\ \mathrm{ps}^{-1}$ (semileptonic)

$\Delta m_d = 0.516 \pm 0.016 \pm 0.010\ \mathrm{ps}^{-1}$

single most precise measurements.

$A_{mix}(\Delta t) = (D \cos \Delta m_d \Delta t) \otimes \Sigma(\Delta t)$



Fit Strategy

Combined unbinned Maximum Likelihood Fit to Δt spectra of Flavor and CP sample

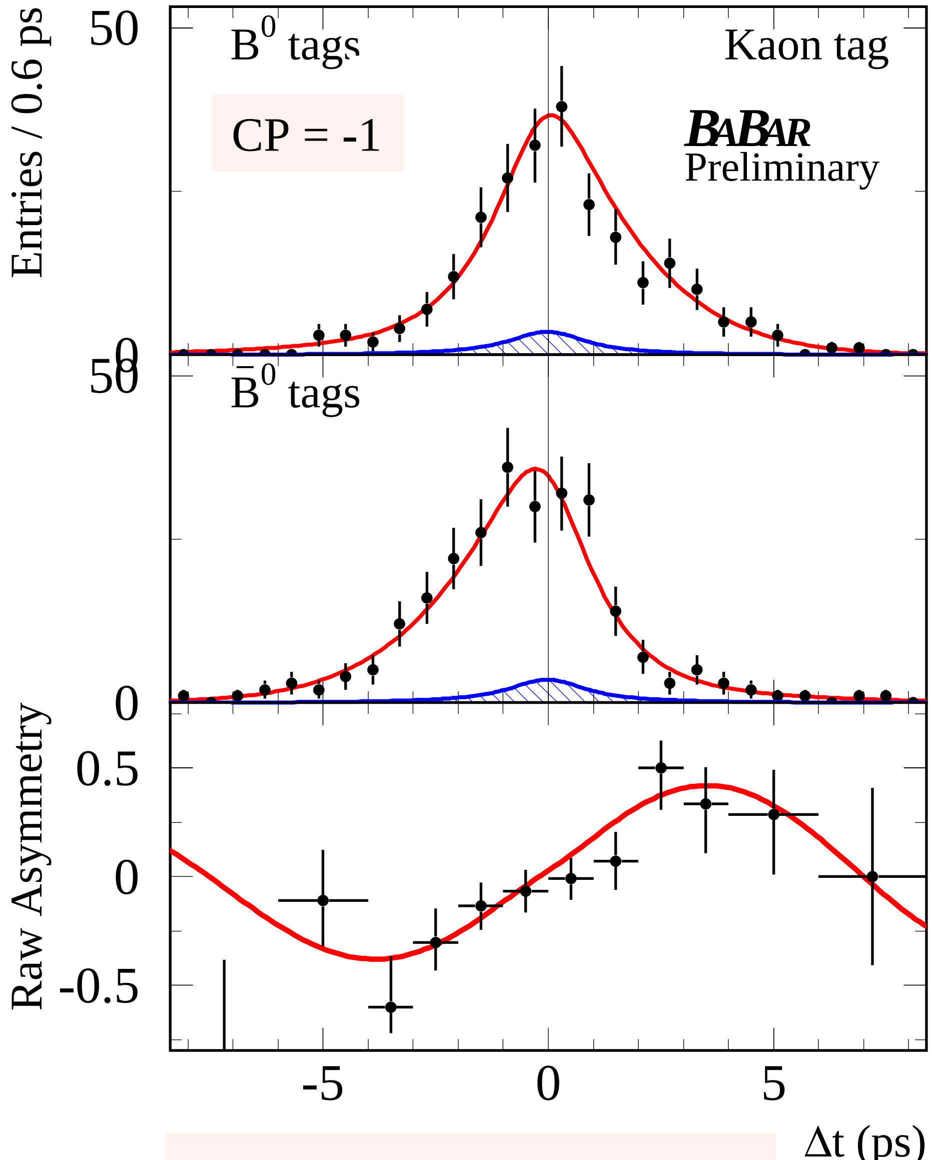
Fit Parameters

S	1	Tagged CP Sample
C	1	
Mistag fractions for B^0 and $\overline{B}^0$ tags	8	Tagged Flavor Sample
Signal resolution function	8	
Empirical description of background Δt	17	
B lifetime fixed to the PDG value	τ_B = 1.548 ps	
Mixing Frequency fixed to the PDG value	Δm_d = 0.472 ps^{-1}	

*Max. correlation of sin 2β with other param: 14%

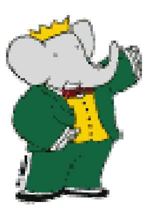
Sin2β Result - CP=-1, Kaon Tag

BABAR
56 fb^{-1}



Raw CP asymmetry

sin2β = 0.75 ± 0.14



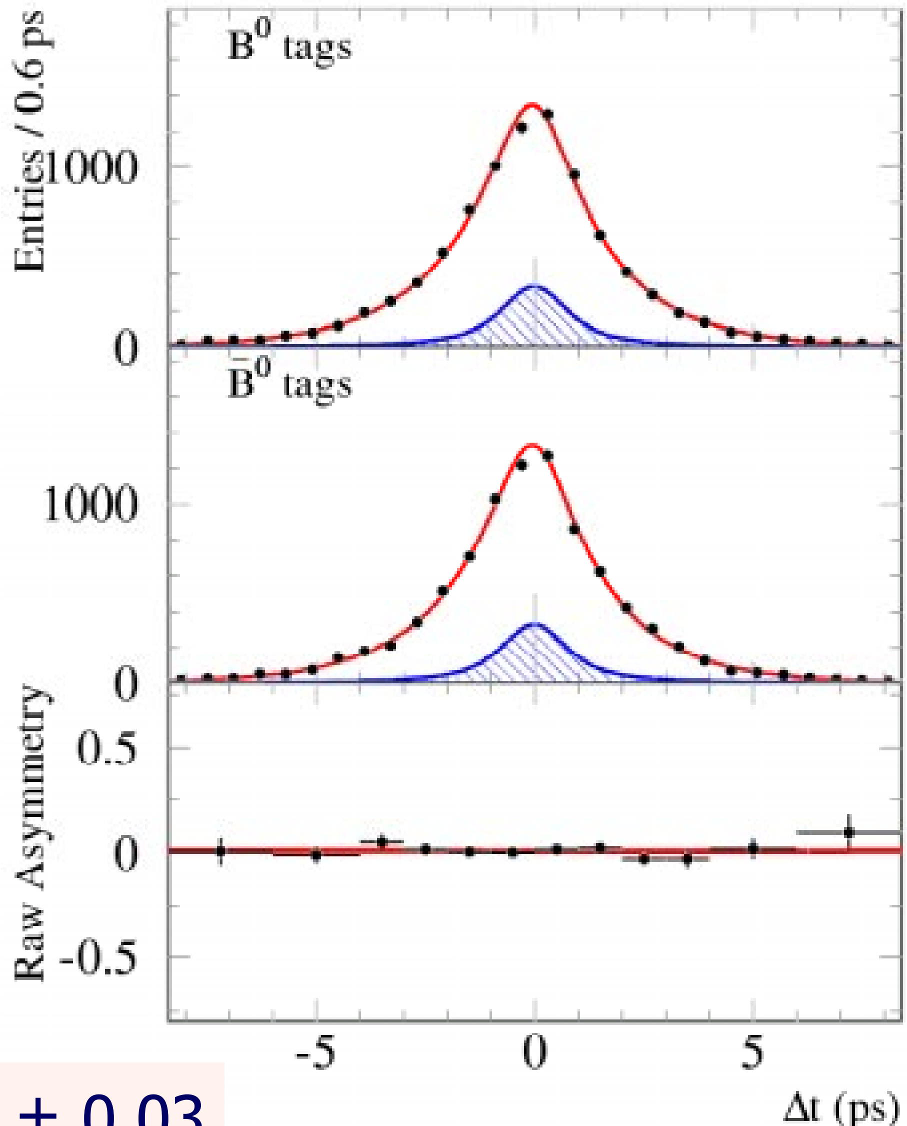
Sin2β Result - Flavor Sample

BABAR
56 fb^{-1}

Check for bias in sin2β fit by treating B_{flav} (mixing) sample same way as CP sample.

CP asymmetry not expected
and not observed.

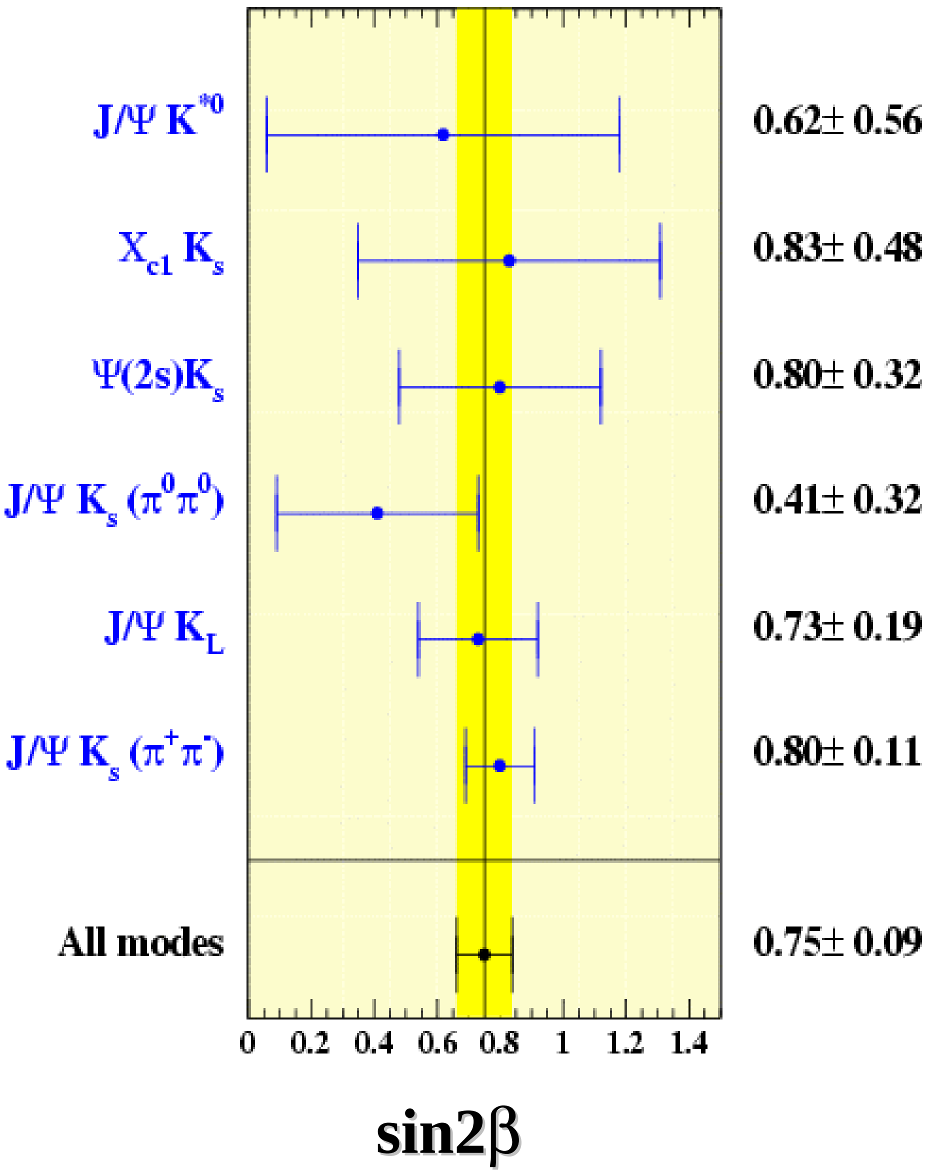
√



$\sin 2\beta = 0.00 \pm 0.03$

Sin 2β - Mode by Mode

BABAR
56 fb^{-1}



Systematic Error

Δt measurement (0.01)

- residual uncertainties in SVT alignment

Δt resolution function (0.01)

- difference between CP and Flavor set

Δm_d and lifetime knowledge (0.02)

Background properties (0.02)

- level (m_{ES} shape)
- composition (B^+ content)
- CP asymmetry in background

Mistag fraction (0.007)

- differences B_{CP} versus B_{FLAV} samples

$\Rightarrow$ $\boxed{\sigma = 0.04}$ **for the full sample**

~13% improvement in statistical error to previous measurement [naïve: $\sigma(\sin 2\beta) = 0.14 \times \mathrm{sqrt}(30\mathrm{fb}^{-1}/56\mathrm{fb}^{-1})$].

Probing New Physics

In case more than one weak decay phase present

$\Rightarrow$ additional $cos(\Delta m \Delta t)$ term in decay distribution

CP violation modified:

$$\boxed{R(\Delta t) \propto exp(-|\Delta t|/\tau_B)\ (\ 1 \pm S\ sin(\Delta m \Delta t) \mp C\ cos(\Delta m \Delta t)}$$

S = sin 2β ?

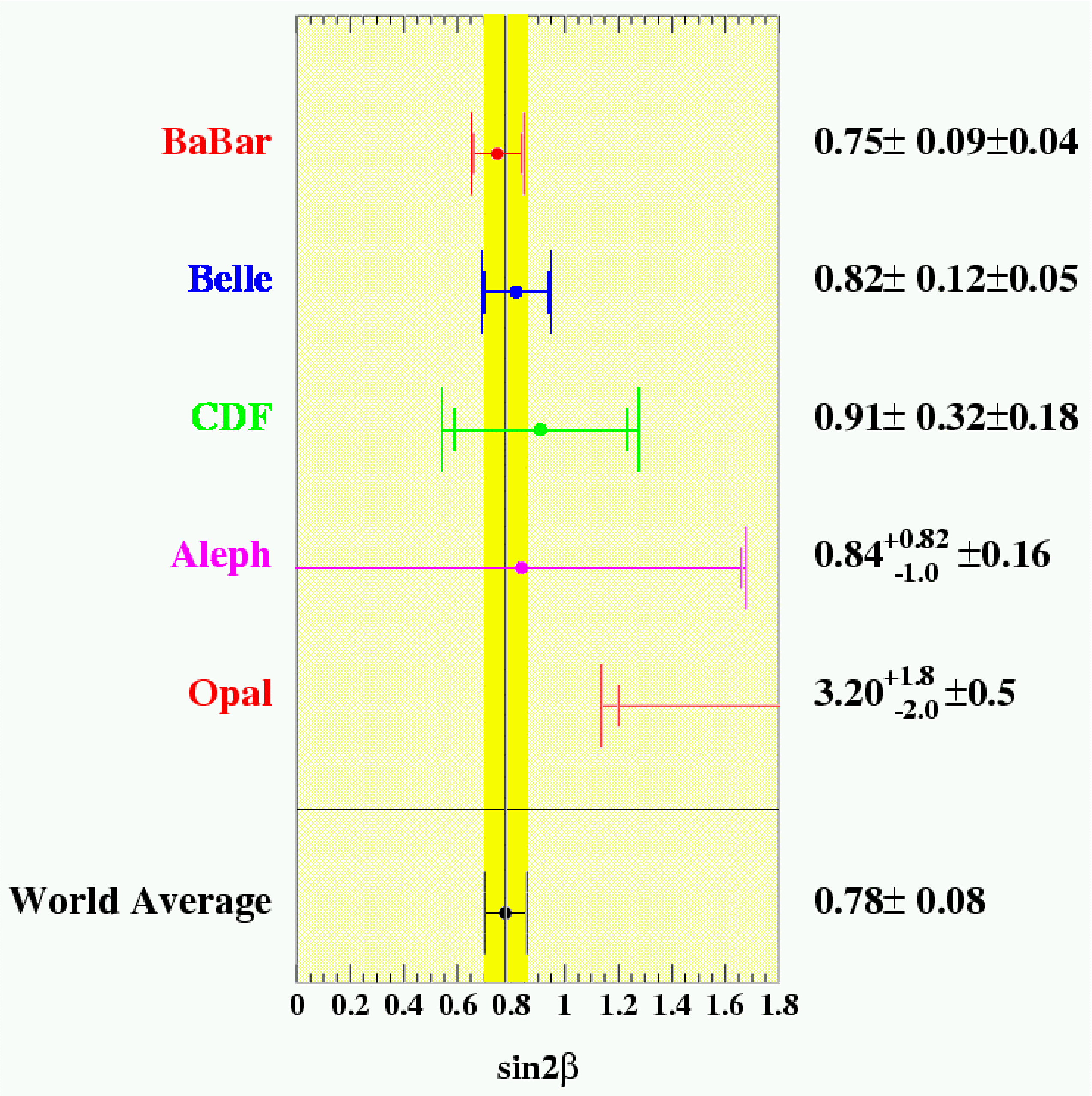
new physics decay ?

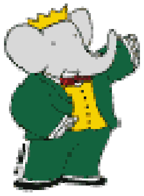
Fit with η_{CP}=-1 sample:

$$\boxed{C = 0.083 \pm 0.065\ (\text{stat.}) \pm 0.022\ (\text{syst.})}$$

S remains unchanged

Sin 2β – World Average





Toy MC test for ϕK_S in $100 fb^{-1}$

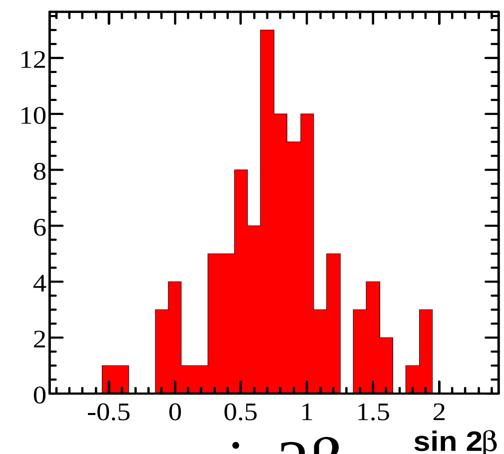
Fit BF $\otimes$ CP :

Signal = 60, background = 1915, $\sin 2\beta$ = 0.7

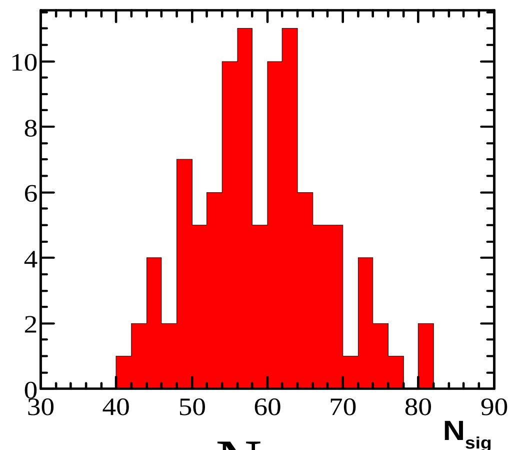
Allow no-tag category

PDFs from BF fit and for CP side modeled on the flavor sample

100 samples:



$\sin 2\beta$

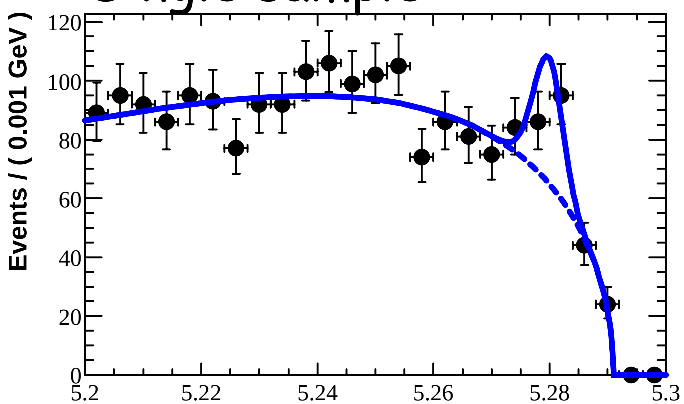


N_{sig}

$$\sin 2\beta(\phi K_S) = 0.76^{+0.45}_{-0.51}$$

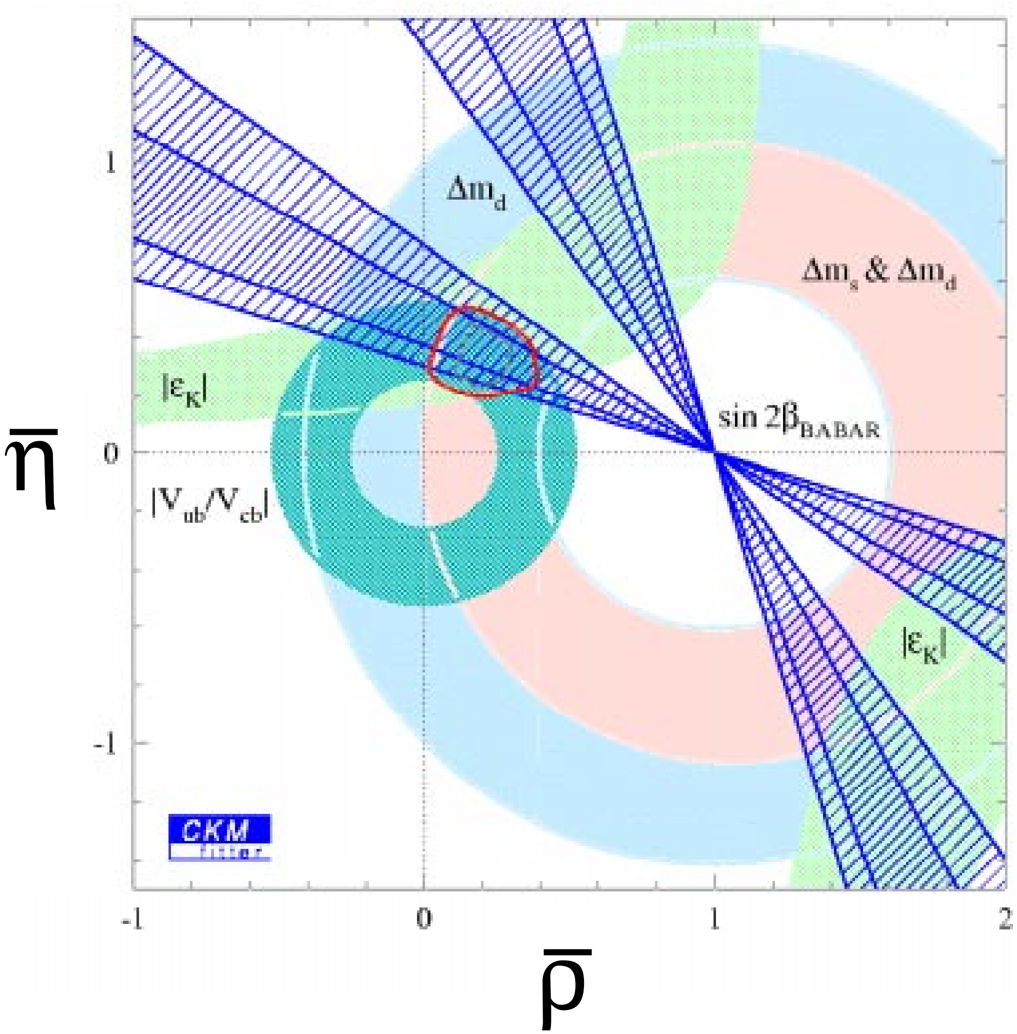
$$N_{sig}(\phi K_S) = 59^{+8.5}_{-7.8}$$

Single sample:

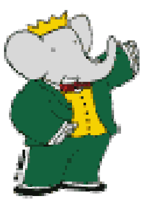


m_{ES} [GeV]

CKM Interpretation



- sin2β measurement is consistent with current SM constraints
- no new physics in mixing



[Höcker et al, Eur.Phys.J.C21:225-259,2001 or other recent CKM fits)]

Summary

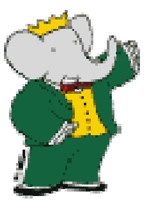
- BaBar measures time-dependent CP-violating asymmetries in neutral B decays at the $\Upsilon(4S)$ resonance with very high precision.
- We have observed CP violation in the B^0 system at the 7.6 σ level

$$\boxed{\sin(2\beta)=0.75\pm0.09\pm0.04}$$

- The value is consistent with other experimental constraints on the Standard Model.
- BaBar is well suited to measure $\sin2\beta$ in the pure penguin channel ϕK^0.
- In $100\mathrm{fb}^{-1}$ we expect: $\sigma(\sin2\beta)_{J/\Psi} \sim 0.07$

  $\sigma(\sin2\beta)_{\phi} \leq 0.50$ (~ 0.35 with all ϕ,η' modes)

  $\Delta(\sin2\beta)_{\text{Theory}} < 0.04$ (< 0.15) .



Outlook