Measurement of CP asymmetry in B Decay with the BaBar Detector

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for the BaBar collaboration

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(I) Introduction to CP Violation

Why is CP violation interesting

- It is of fundamental importance
  - Needed for matter-antimatter asymmetry in the universe
- History tells us that studying symmetry violation can be very fruitful

- Conventional wisdom: Standard Model CP-violation is unlikely to explain matter asymmetry in the universe
  - It means there is something beyond SM in CP violation somewhere, so a good place to work

History of CP violation

1964: CP Violation Observed in Kaon decays (Nobel)
Wolfenstein postulated the existence of a new force, called SuperWeak, that generated *CP* violation in K^0–$\overline{K}^0$ mixing and practically nothing else observable

1973: Kobayashi and Maskawa observed that *CP* could be violated in the weak interaction with quarks if there were AT LEAST 3 generations of quarks (only 2 known at the time)

1975: τ lepton discovery starts the 3rd lepton generation (Nobel)

1977: The *b* quark was discovered ⇒ start of the 3rd quark generation (Nobel)

1981: The Bd meson was discovered, lifetime found long ~ 1ps

1986: Large Matter-Antimatter oscillation was observed in Bd decay

1993: The B_s mesons was discovered, huge Oscillation frequency

1995: The *t* quark discovered ⇒ Completes the third quark generation

2000: ν_τ discovered at Fermilab, completes third lepton generation

2001: Dedicate B-factory experiments BaBar&Belle publish first results on sin2β

CP Violation in the Standard Model

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

CKM matrix

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

Wolfenstein parameterization

Complex phase

? = $\sin(\theta_{\mathrm{cabbibo}}) \approx 0.22$

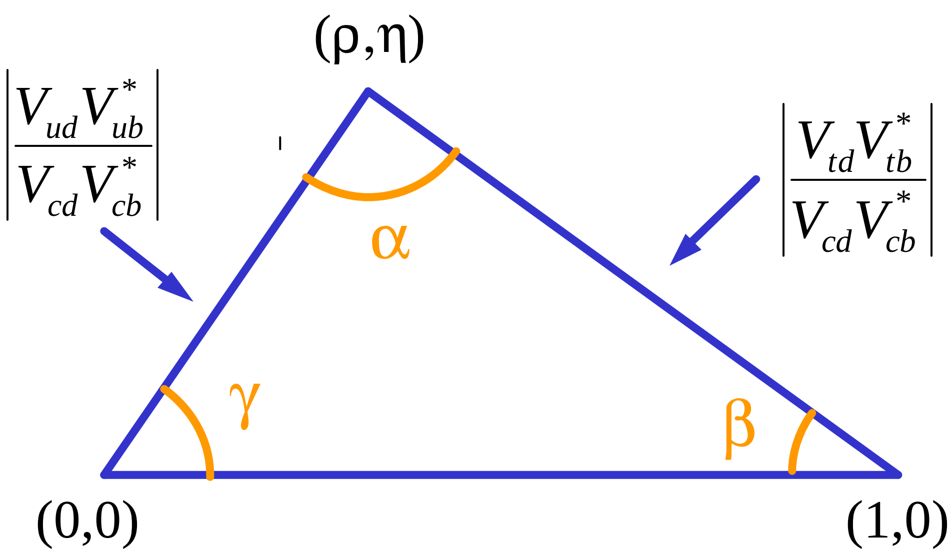
- V has only 4 independent number in SM
  - commonly expressed in the Wolfenstein parameterization
- Standard model with 3 generations accommodates CP violation through a phase in the CKM matrix

Expressing Unitarity constraints: Unitarity Triangles

- Unitarity constraint on the CKM matrix gives 9 constraining relations on the matrix element.
- Example: Constraint on the 1st and 3rd columns of V.

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

- Align $V_{cd}V^{*}_{cb}$ with the real axis
- Renormalize sides by $|V_{cd}V^{*}_{cb}|$



- All side of order λ^3
- Magnitude of CP violation $\propto$ triangle area
- Unitarity test: Does the triangle close?

(II) The B^0_d system as CP laboratory

Why Study CP violation in the B system

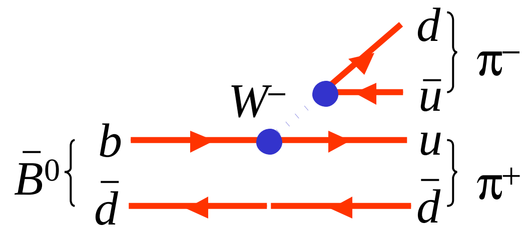
Quark content of the B system

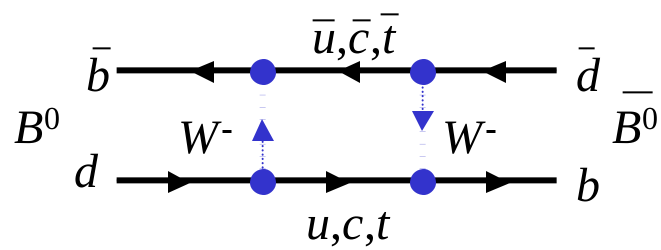
$$B^0 = \bar{b}d, \quad \overline{B^0} = b\bar{d},$$
$$B^+ = \bar{b}u, \quad B^- = b\bar{u}$$

- SM predicts a variety of CP violating asymmetries in the B system
- Some of these can be cleanly interpreted in term of CKM matrix elements (= parameters of the SM Lagrangian)
- Asymmetries expected to be large
- B^0 mesons can be produced and detected easily

CP Violating Observables

- In order to generate a CP violating observable, we must have the following conditions:
  - Interference between at least two different amplitudes
- In B decays, we can consider two different types of amplitudes:
  - Those responsible for **decay**
  - Those responsible for **mixing**





- This gives rise to three possible manifestations of CP violation:
  - **Indirect CP violation**
    - (interference between two mixing amplitudes)
  - **Direct CP violation**
    - (interference between two decay amplitudes)
  - **CP violation in the interference between mixed and unmixed decays**

Direct CP Violation

- We observe CP violation in decay if

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f})$$

  - In SM, CP conjugates of each amplitude can only differ by a phase factor: CP $A_{B\to f}$ = exp(-if) $A_{B\to f}$

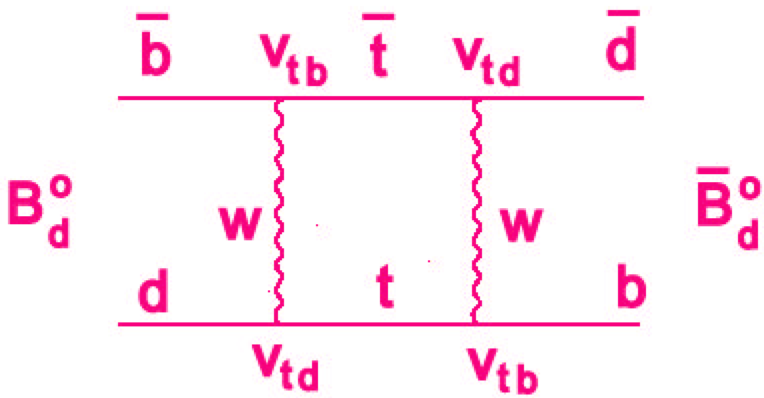
- Conditions for CP violation in decay
  - There exist at least 2 amplitudes for this decay, e.g.

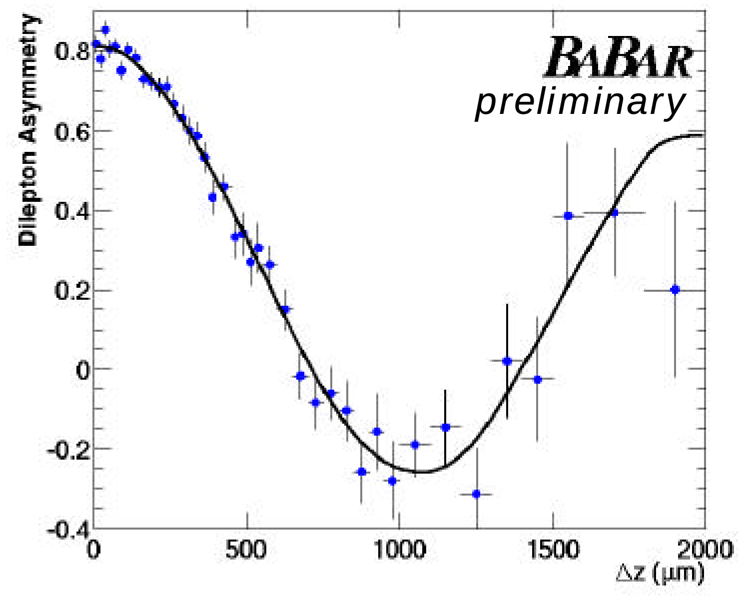
$$\Gamma(B \to f) = |A_1 + A_2|$$

  - Amplitudes must have 2 phases: CP $A_{B\to f} = e^{-i\,(d_f + f_f)}\, A_{B\to f}$
    - **A strong phase (doesn't change sign under CP)**
    - **A weak phase (flips sign under CP)**
  - Strong and weak phases must be different, amplitudes must be similar
  - CKM Interpretation of observed direct CP violation difficult
    - Theoretical calculations of strong phase complicated

Indirect CP violation: B^0-B^0 mixing

- B^0 and $\overline{B^0}$ oscillate into each other with a frequency that is experimentally accessible!
  - Second order weak transition
  - Oscillation frequency determined by $M(B^0) - M(\overline{B^0}) \equiv \Delta m_d \approx 0.5\ ps^{-1}$

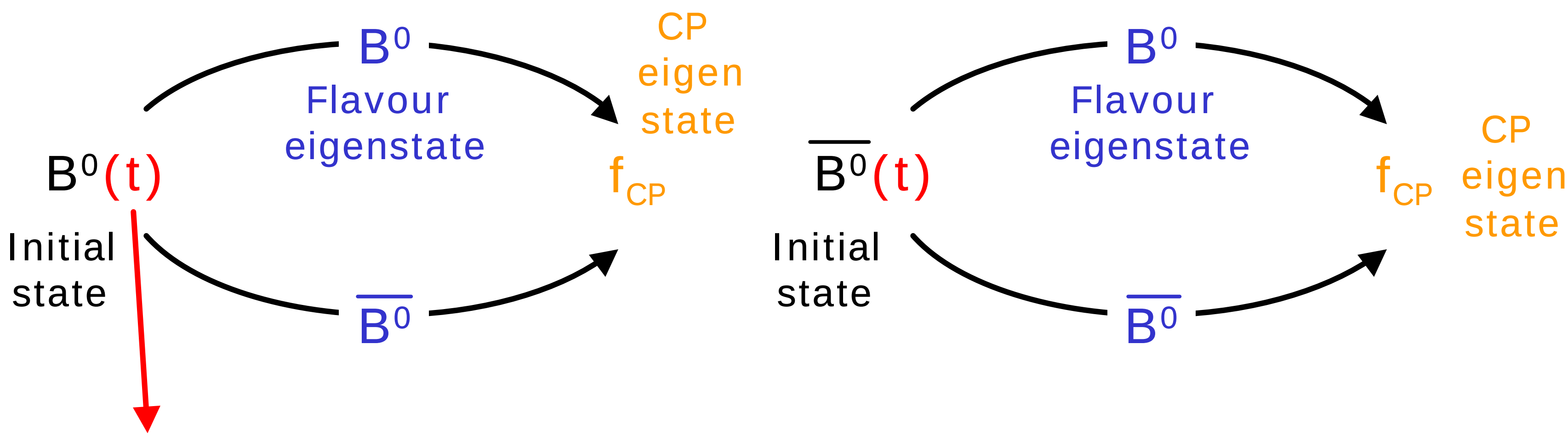




  - Condition for CP violation in mixing: $|\langle B^0|H|\overline{B^0}\rangle| \neq |\langle \overline{B^0}|H|B^0\rangle|$
  - Mixing dominated by diagram with top quark
    $\rightarrow$ magnitude of CP violation $\propto (m_b/m_t)^2 << 1$
  - **CP violation in mixing negligible in B system**

CP Violation in Interference between Mixing and Decay

- Observe 2 processes leading to the same CP eigenstate via intermediate flavour eigenstate



- Time evolution of $B^0 - \overline{B^0}$ mixing oscillations:

$$|B^0(t)\rangle = e^{-iMt}e^{-\Gamma t}\left(\cos\frac{\Delta m\ t}{2} |B^0\rangle + i \sin\frac{\Delta m\ t}{2} \cdot \frac{q}{p} |\overline{B^0}\rangle \right)$$

$$|\overline{B^0}(t)\rangle = e^{-iMt}e^{-\Gamma t}\left(i \sin\frac{\Delta m\ t}{2} \cdot \frac{p}{q} |B^0\rangle + \cos\frac{\Delta m\ t}{2} |\overline{B^0}\rangle \right)$$

$p/q \approx 1$

$$|B_\pm\rangle = p|B^0\rangle \pm q|\overline{B^0}\rangle$$

CP Violation in interference between mixing and decay

- Probability to observe CP eigenstate f_{CP} at time t:

$$F_-(t) \equiv |\langle f_{cp}|H|B^0(t)\rangle|^2 = e^{-\Gamma t}\,|A|^2 \left[\frac{1}{2}(1+|\lambda|^2) + \frac{1}{2}(1-|\lambda|^2)\cos\Delta m\, t - \mathrm{Im}\,\lambda\cdot\sin\Delta m\, t\right]$$

$$F_+(t) \equiv |\langle f_{cp}|H|\overline{B^0}(t)\rangle|^2 = e^{-\Gamma t}\,|\overline{A}|^2 \left[\frac{1}{2}(1+|\lambda|^2) - \frac{1}{2}(1-|\lambda|^2)\cos\Delta m\, t + \mathrm{Im}\,\lambda\cdot\sin\Delta m\, t\right]$$

$$\lambda = \eta_{cp}\,\frac{q}{p}\,\frac{\overline{A}}{A}$$

Amplitude ratio $B^0 \to f_{cp} / \overline{B^0} \to f_{cp}$

CP eigenvalue

$|B_\pm\rangle = p|B^0\rangle \pm q|\overline{B^0}\rangle$ ≈1

- Observable CP asymmetry $A_{cp}(t) = (F_+(t) - F_-(t)) / (F_+(t) + F_-(t))$

$$A_{cp}(t) = \frac{-(1-|\lambda|^2)\cos\Delta m\, t + 2\,\mathrm{Im}\lambda\,\sin\Delta m\, t}{1+|\lambda|^2} \quad \left(= \mathrm{Im}\,\lambda\cdot\sin\Delta m\, t \right)$$

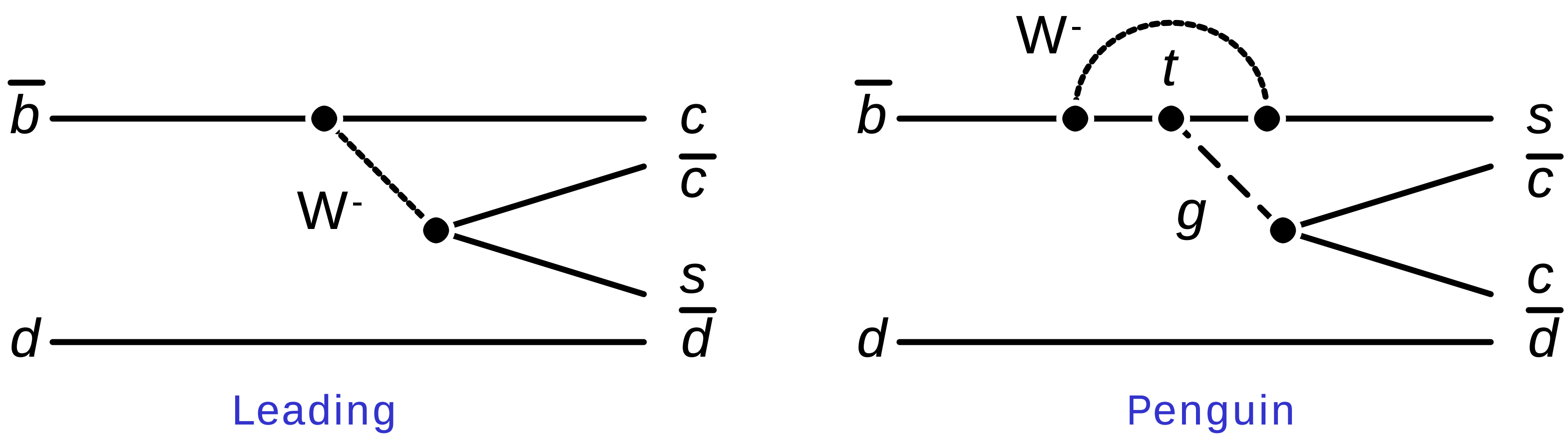
When |?|=1

–CP asymmetry is **time dependent**

–Need $|\lambda| \neq 1$ or $\mathrm{Im}\lambda \neq 0$ to observe CP violation, SM predicts |?|=1

Golden Mode for CP Violation in mixing/decay interference

- Dominant amplitudes for b $\rightarrow$ c$\bar{c}$s decay:



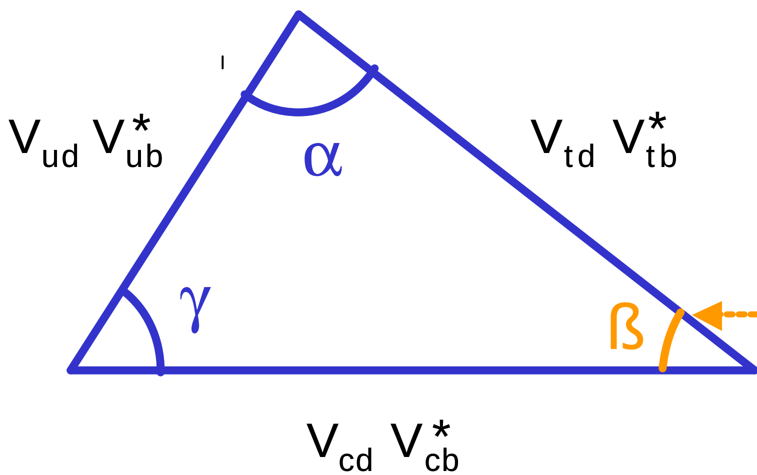
- Both amplitudes have the same weak phase: $A \propto V_{cb}^{*} V_{cs}$
  no other amplitudes for this decay with competing magnitude
  - No CP violation in decay expected in SM
- CP violation in mixing also negligible because Γ_{12}<<1
- Standard Model CP violation (if there is any) is entirely due to interference between mixed and direct decay amplitudes

CKM interpretation of Golden Mode

- For the mode B^0 → J/? K^0 , K^0 mixing is required

$$\lambda = \eta_{cp}\,\frac{q}{p}\,\frac{\overline{A}}{A}\left(\frac{q}{p}\right)_K = \eta_{cp}\underbrace{\left(\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}\right)}_{B^0\ \text{mixing}}\underbrace{\left(\frac{V_{cb}\cancel{V_{cs}^{*}}}{V_{cb}^{*}\cancel{V_{cs}}}\right)}_{\text{Decay}}\underbrace{\left(\frac{\cancel{V_{cs}}V_{cd}^{*}}{\cancel{V_{cs}^{*}}V_{cd}}\right)}_{K^0\ \text{mixing}} = \eta_{cp}\,e^{-2i\beta}$$

$A_{cp}(t)$ = Im? sin (? m t) → $\boxed{A_{cp}(t)\ =\ ?_{cp}\ \sin(2ß)\ \sin(?\,m\ t)}$

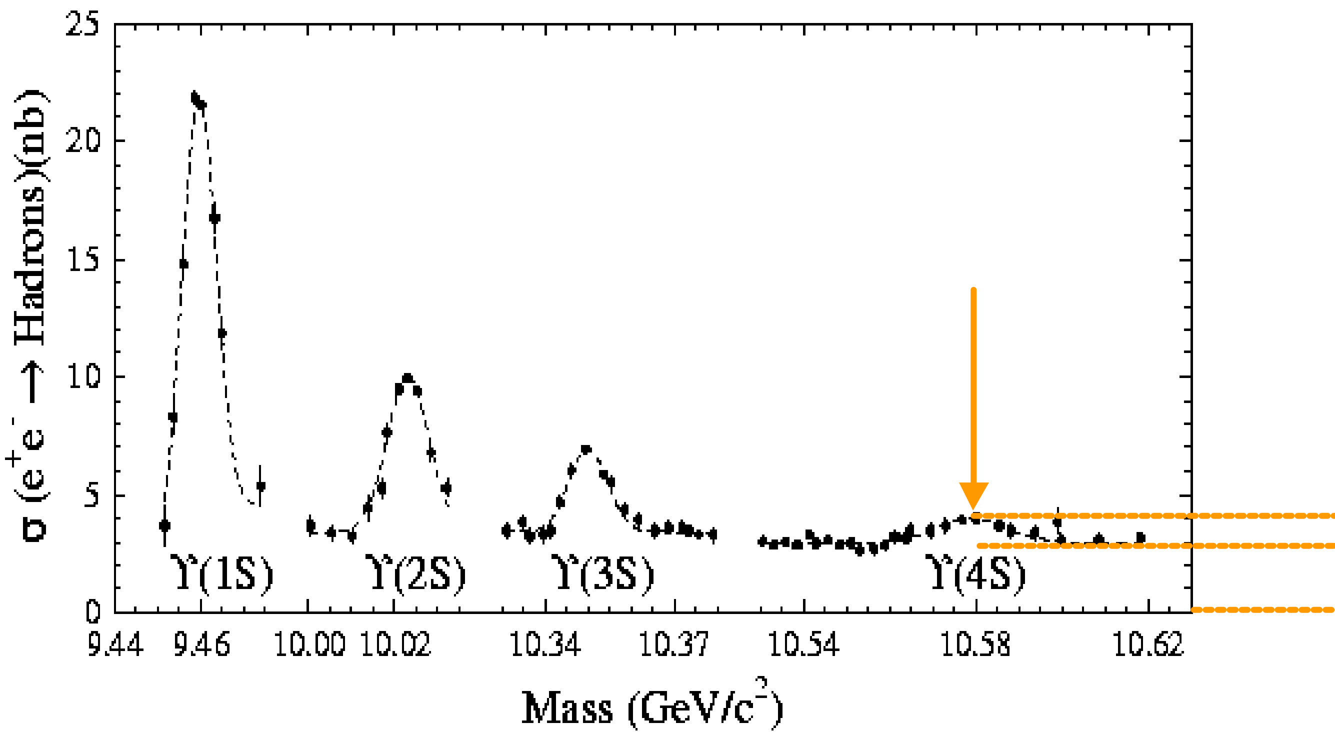


(II) Experimental requirements and setup

B^0 meson production

- Electron-Positron collider: $e^+e^- \rightarrow ?(4s) \rightarrow B^0\overline{B^0}$
  - Only 4s resonance can produce B meson pair
  - Low B^0 production cross-section: ~1 nb
  - Clean environment, coherent $B^0\overline{B^0}$ production

B-Factory approach



$$\frac{s\left(b\bar{b}\right)}{s\left(\mathrm{hadr}\right)} = 0.28$$

Properties of coherent $B^0\overline{B^0}$ production

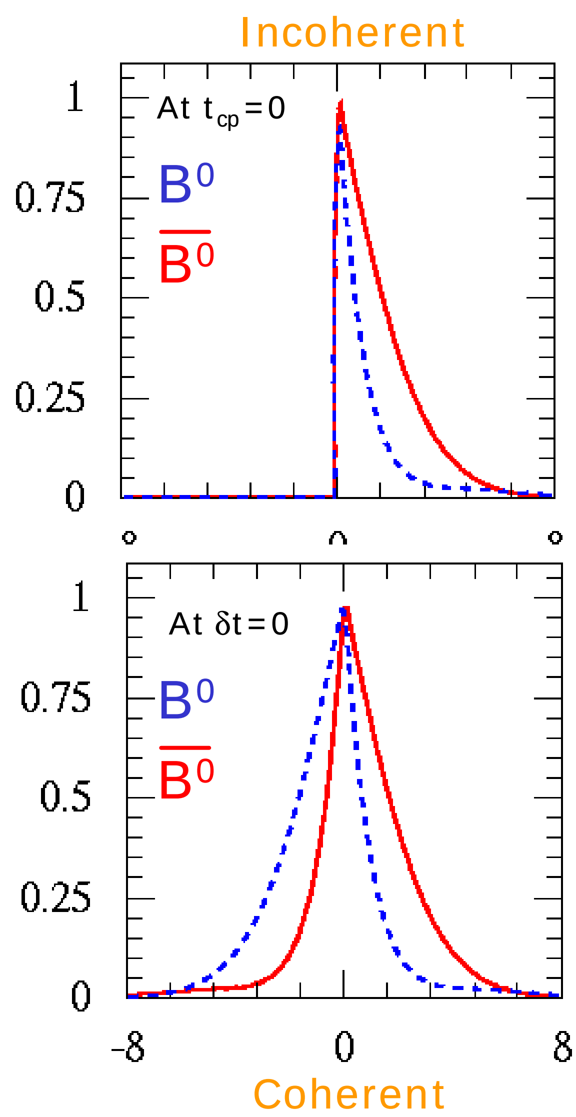
- $B^0\overline{B^0}$ system evolves coherently until one of them decays
  - CP/Mixing oscillation clock only starts ticking at the time of the first decay, relevant time parameter δt:

$$dt = t_{CP} - t_{OtherB}$$

  - Bs have opposite flavour at time dt=0
  - Half of the time CP B decays first ($\delta t<0$)
- Integrated CP asymmetry is 0:

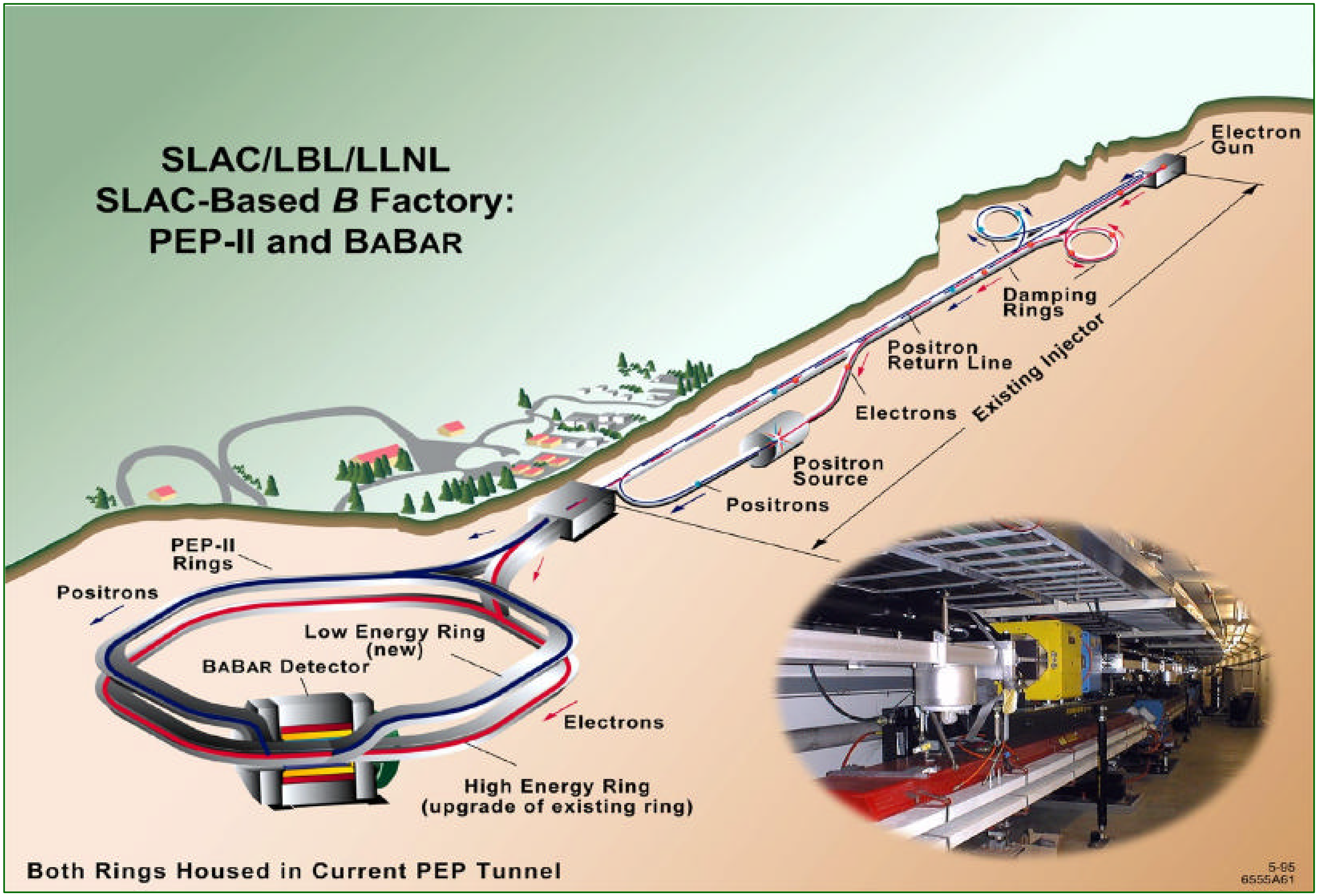
$$\int_{-\infty}^{+\infty} F(t)\, dt = \int_{-\infty}^{+\infty} \overline{F}(t)\, dt$$

- Coherent production requires time dependent analysis



- Large sample of $B^0\overline{B^0}$ events with one fully reconstructed B^0 in CP eigenstate
  - Branching fractions are low, $O(10^{-4})$
  - Need high luminosity collider
- Determine the *initial* flavour of the fully reconstructed B.
  - Determine from decay products of the other B
  - Need good particle ID
- Measure the proper time at decay
  - Momentum of B^0 in Y(4s) rest frame small (~300 MeV), spatial separation of B^0 mesons negligible
  - Use asymmetric collider to produce a boosted Y(4s) to produce a spatial separation of ~250 μm
  - Build high resolution silicon tracker close to interaction point.

The PEP-II storage ring



PEP-II accelerator schematic and tunnel view

PEP-II parameters

Parameter	Design	Achieved
LER energy	3.1 GeV	3.1 GeV
HER energy	9.0 GeV	9.0 GeV
No. of bunches	1658	829
LER current	2140 mA	2140 mA
HER current	750 mA	920 mA
LER lifetime	240 min.	200 min.
HER lifetime	240 min.	660 min.
Beam size x	222 μm	190 μm
Beam size y	6.7 μm	6.0 μm
Luminosity	3 x 10^{33}	**3.1 x 10^{33}**

Boost: $\beta\gamma$ = 0.56

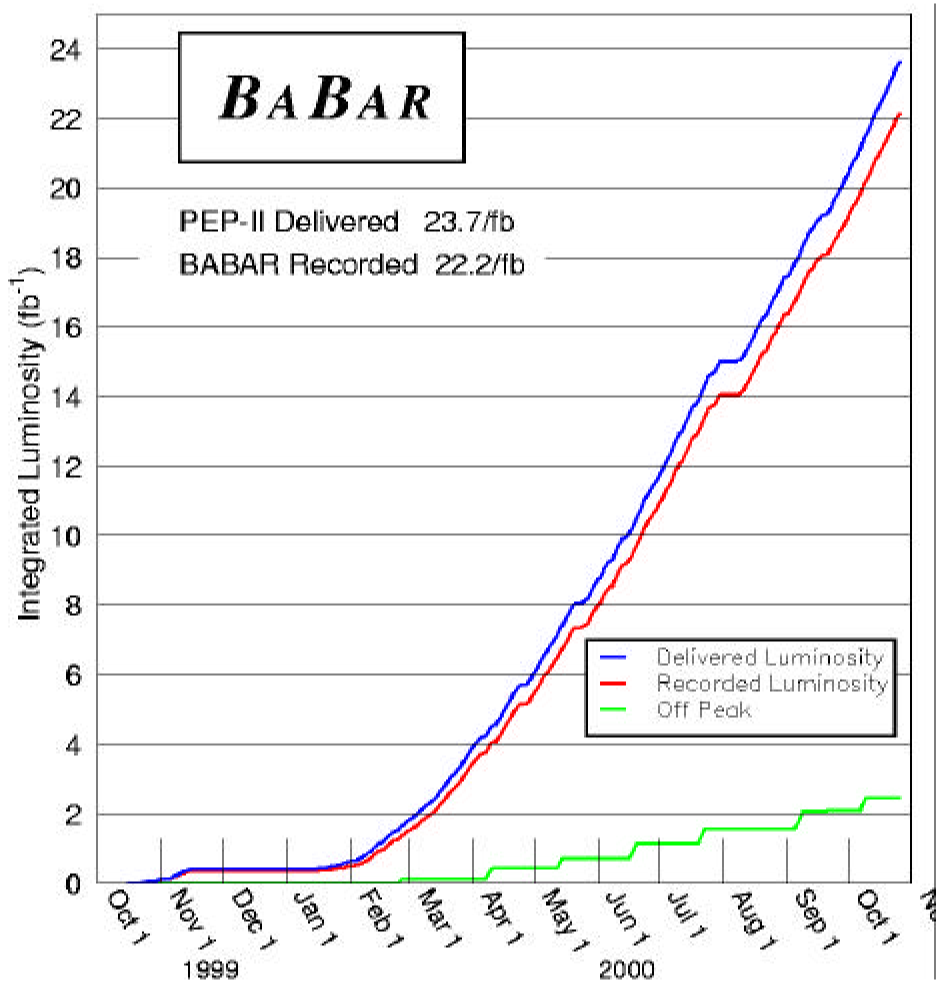
4ns between bunch crossings

High currents

→ 30 $\times$ 10^6 B^0/year

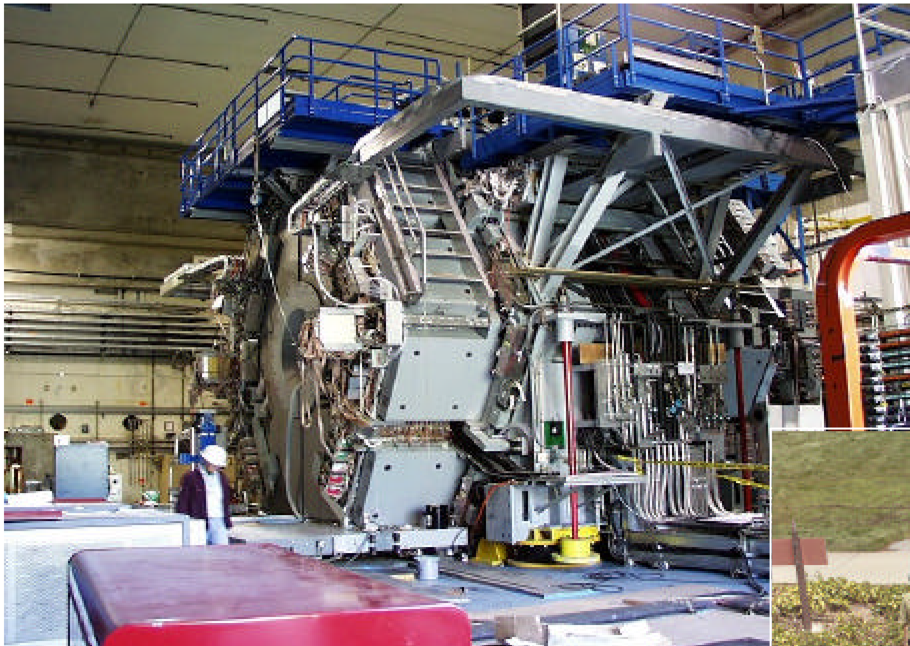
PEP-II Luminosity

- Recorded since May 1999: 20.7 fb^{-1} on Υ(4s) resonance
  - Additional 2.6 fb^{-1} below Υ(4s)
- 22.7 x 10^6 BB pairs
  - Assuming $B^0\overline{B^0}:B^+B^- = 1$



L of 1 fb^{-1} contains (on avg.)
1 event of a process
with a cross section of 1 fb

The BaBar experiment



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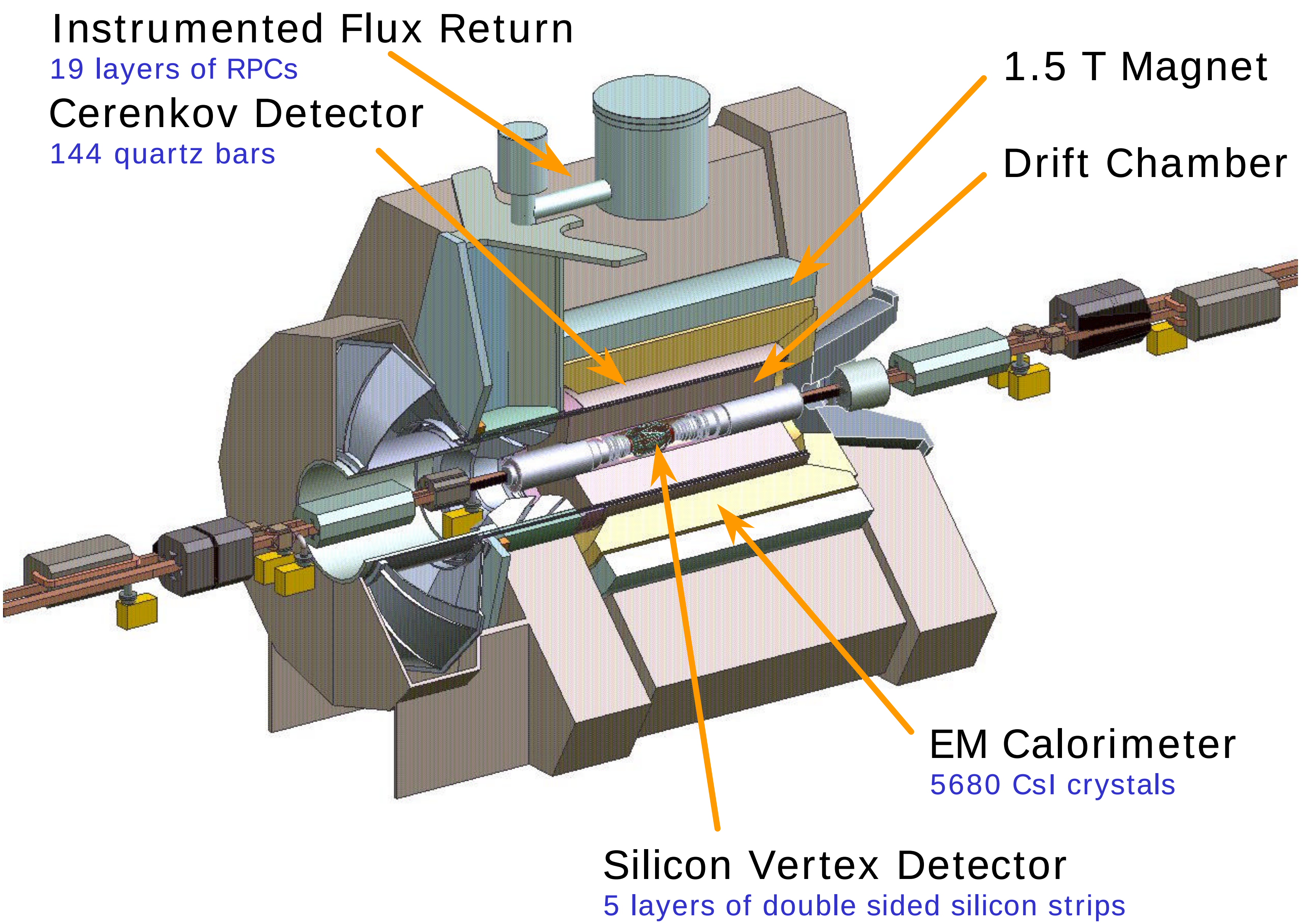
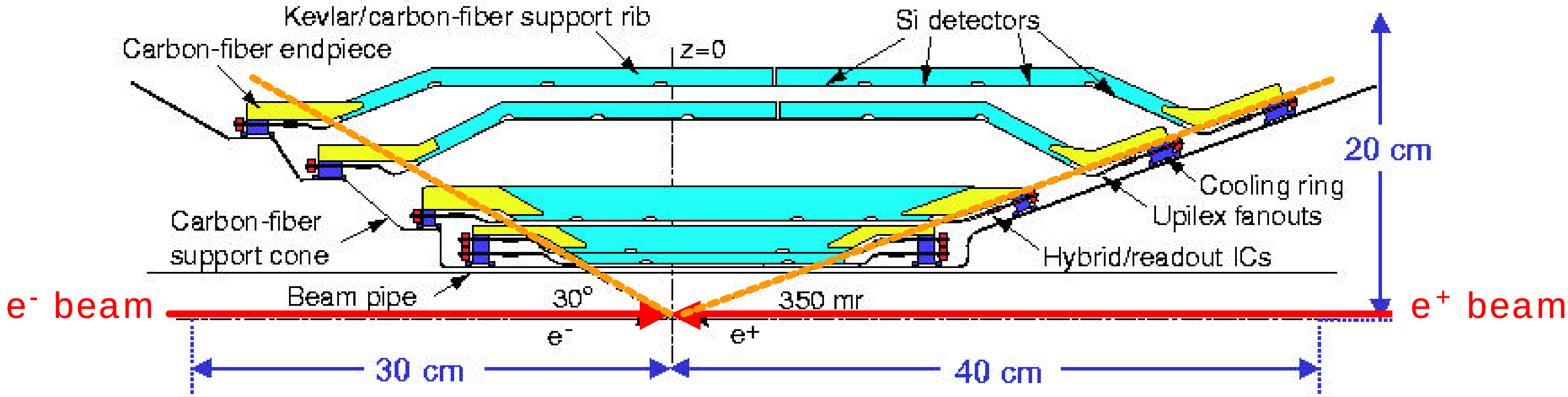
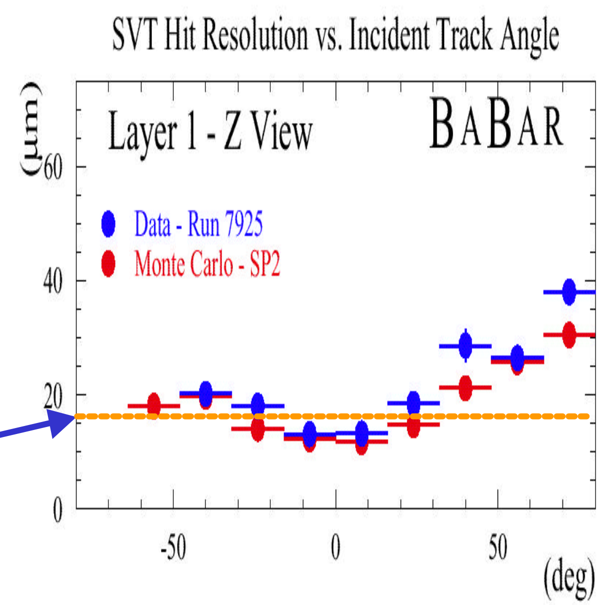
The BaBar detector



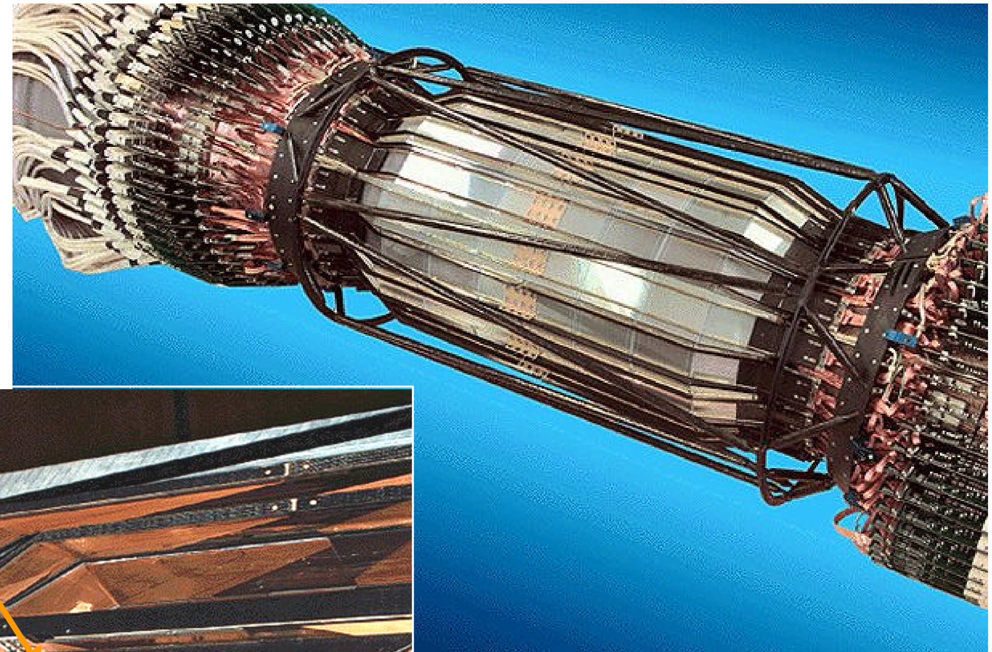
Silicon vertex detector: precise δz measurement

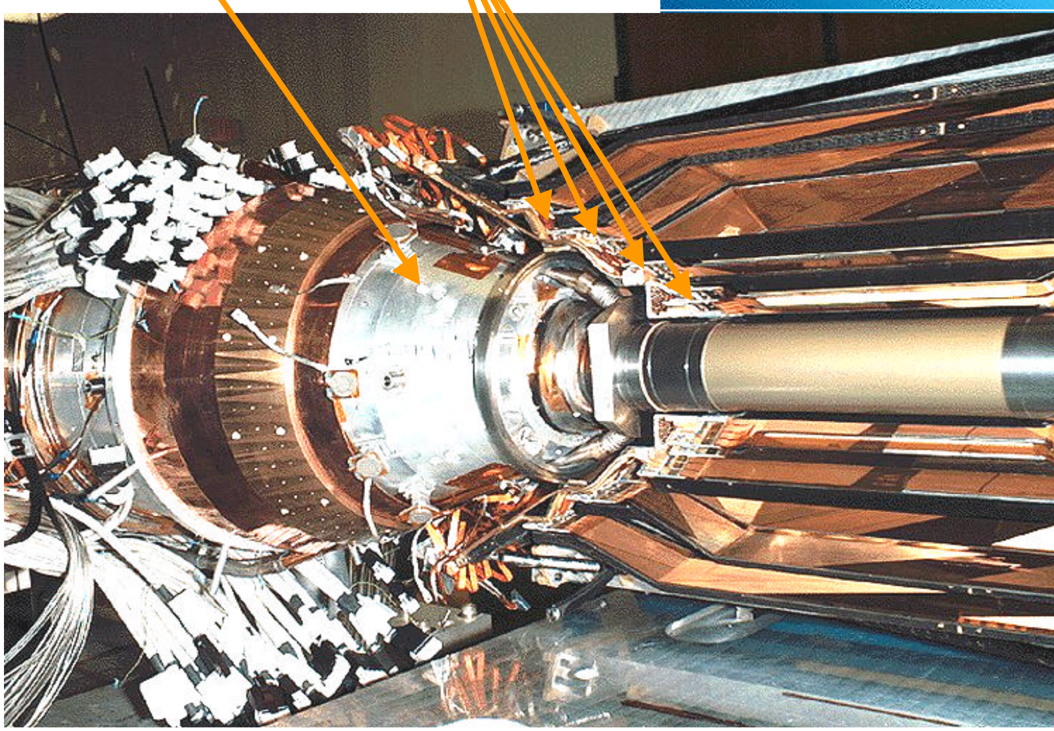


- 5 Layer AC-coupled double sided silicon detector
- SVT Located in high radiation area
  - Radiation hard readout electronics (2Mrad)
- Up to 98% hit reconstruction efficiency
- Hit resolution ~15 μm at 0^0



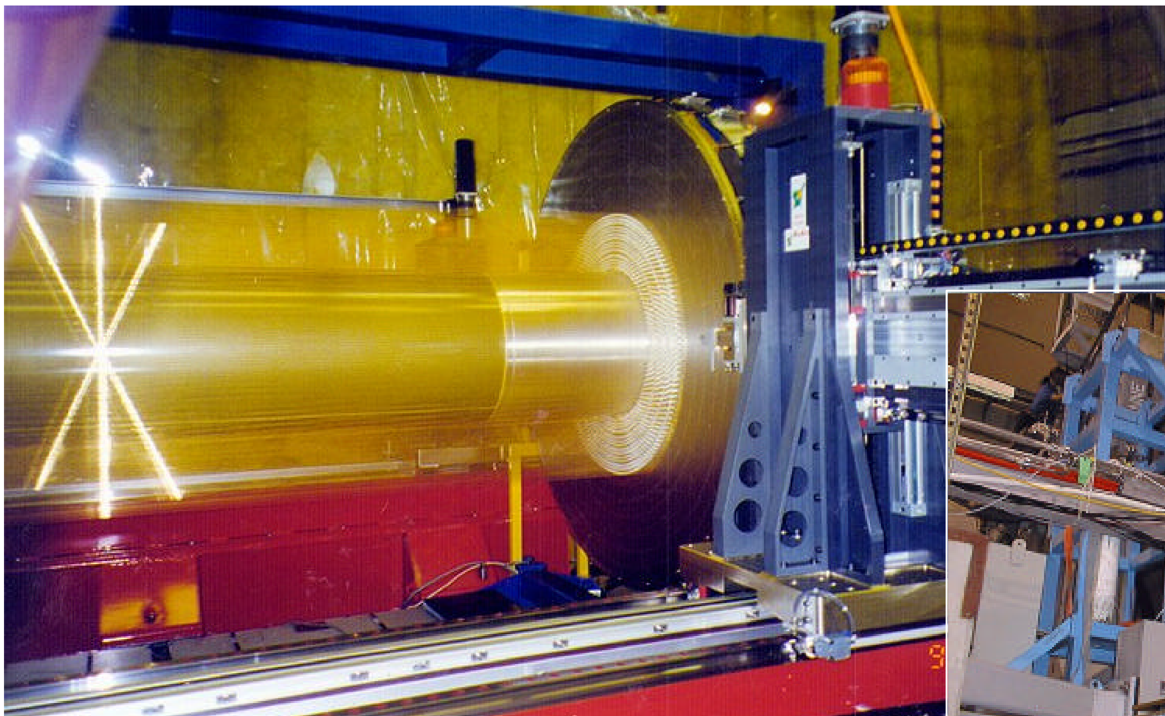
Silicon Vertex Detector

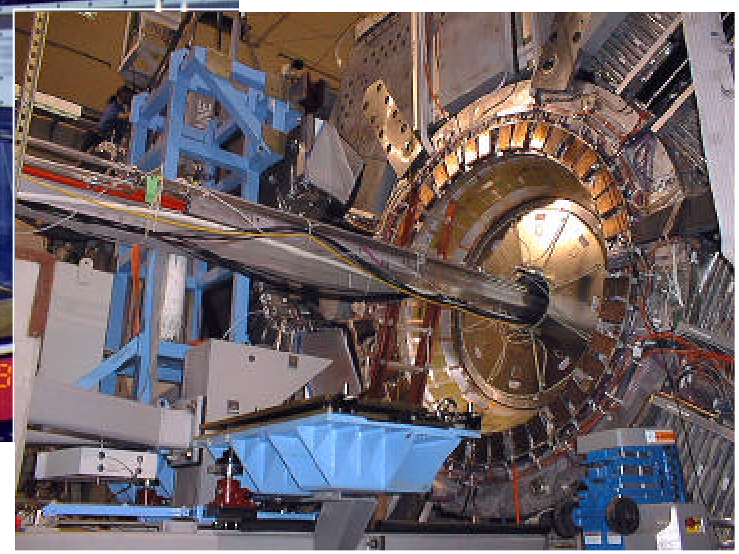




Drift Chamber

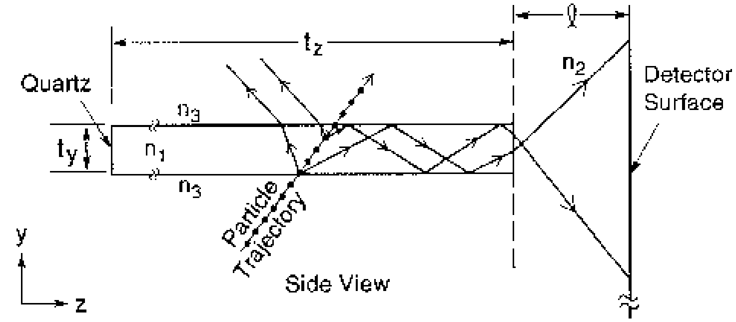
- 40 layers of wires inside 1.5 Tesla magnetic field
- Measurement of charged particle momentum
- Limited particle identification from ionization loss

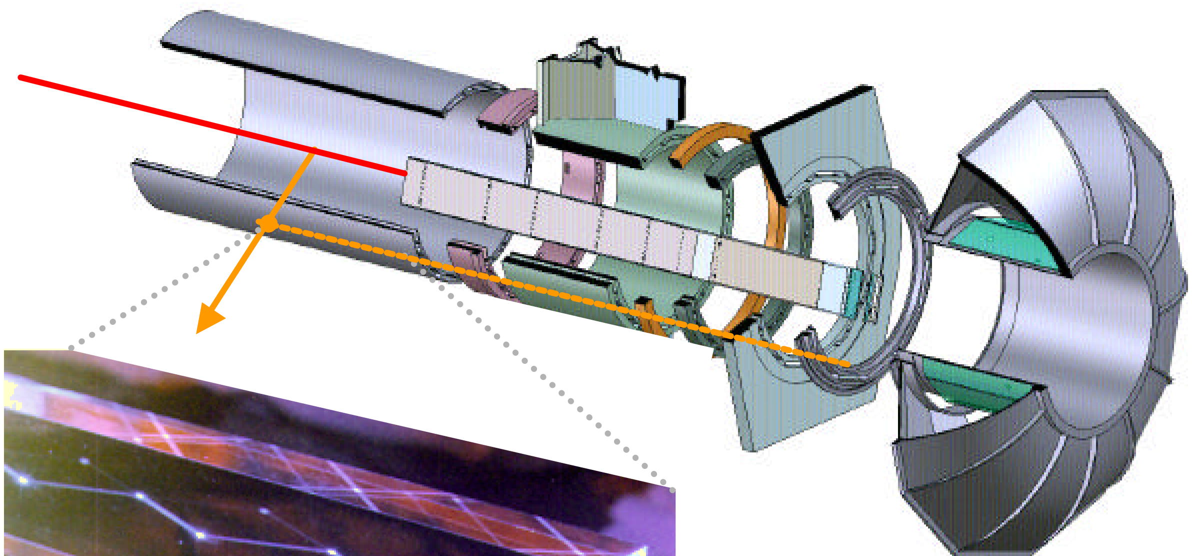


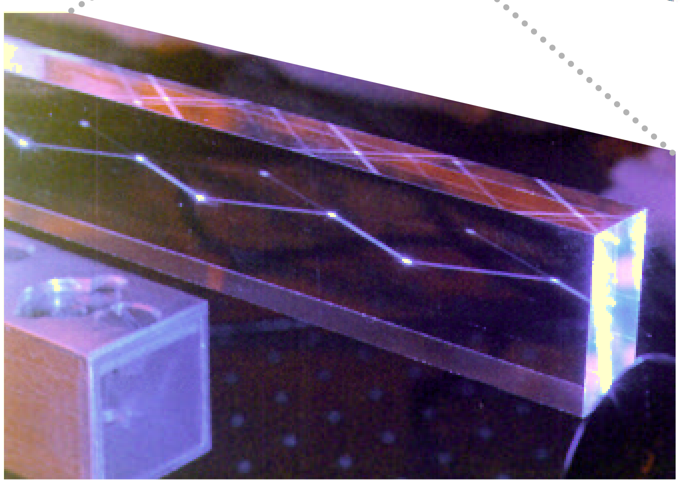


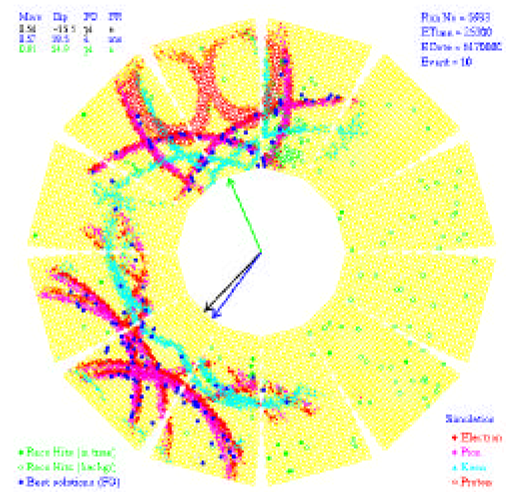
Cerenkov Particle Identification system

- Cerenkov light in quartz
  - Transmitted by internal reflection
  - Rings projected in standoff box
  - Detected by PMTs
  - Essential for Kaon ID >2 GeV





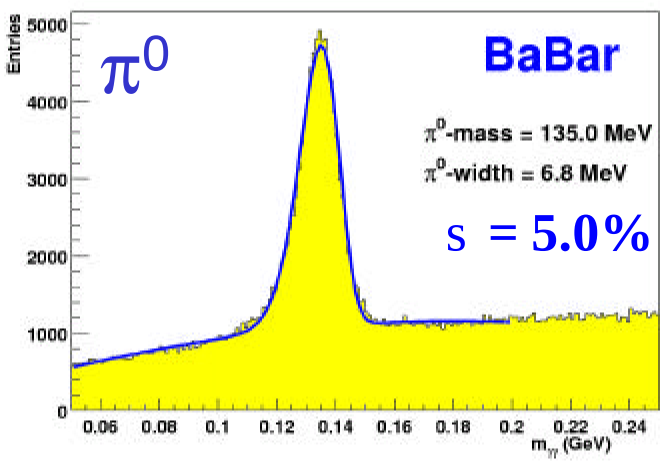


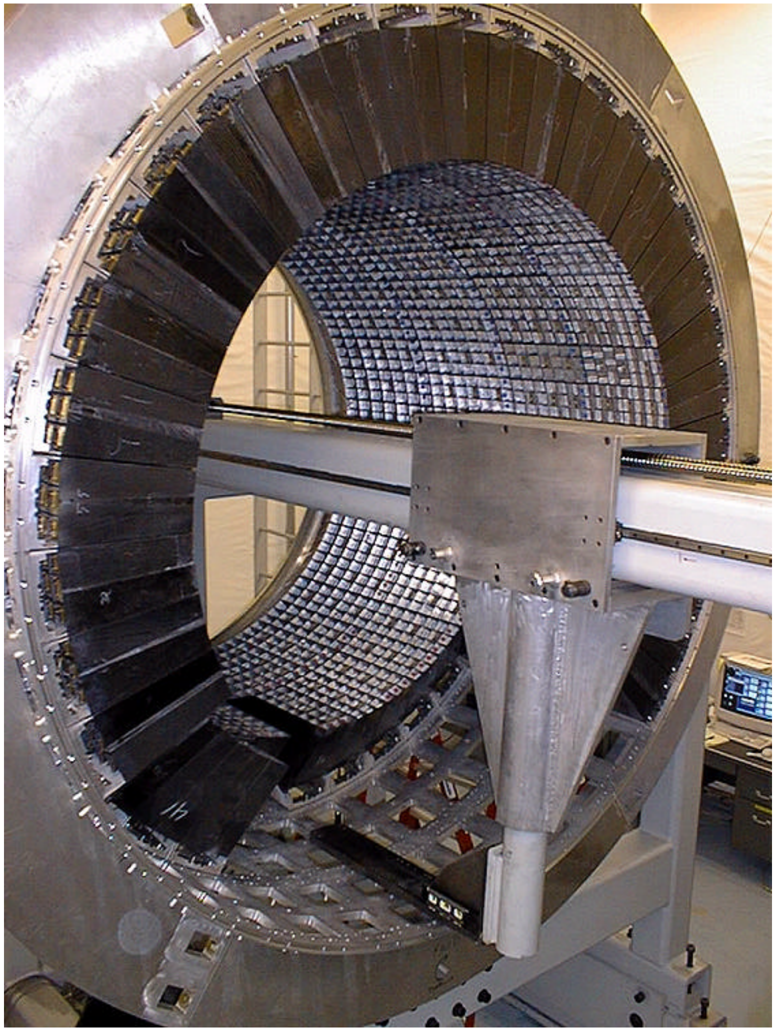


EMC: Electromagnetic calorimeter: $\gamma/\pi^0/e^{\pm}$ ID

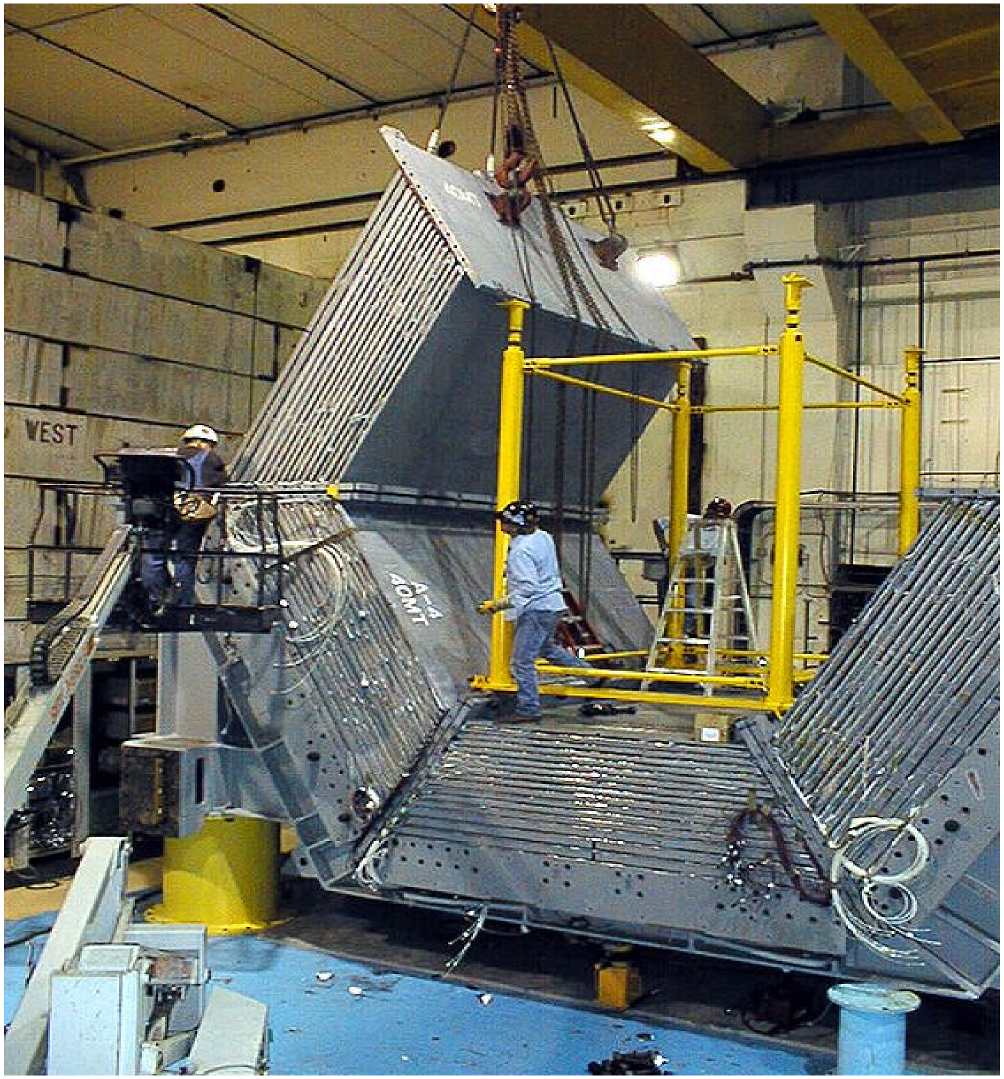
- 6580 CsI(Tl) crystals with photodiode readout
- About 18 X_0, inside solenoid
- Excellent energy resolution, essential for $\pi^0 \to \gamma\gamma$

$$\frac{s\,(E)}{E} = \frac{(2.32 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E}} \oplus (1.85 \pm 0.07 \pm 0.1)\%$$





Instrumented Flux return: $\mu^{\pm}$, K_L identification



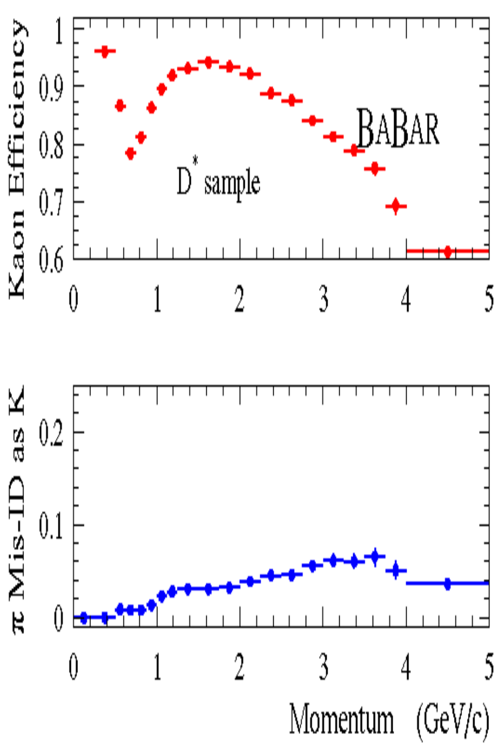
- Up to 21 layers of RPCs sandwiched between iron plates
- Muons identified above 500 MeV
- Neutral Hadrons (K_L) detected

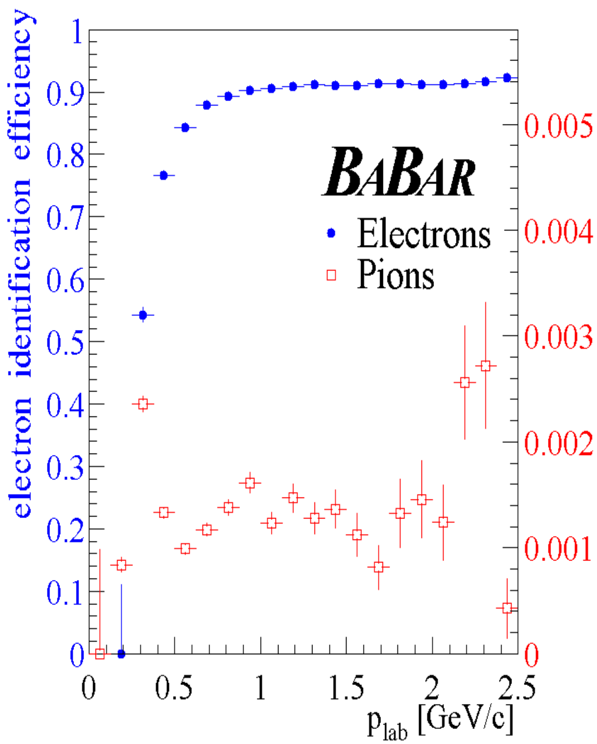
Particle ID performance

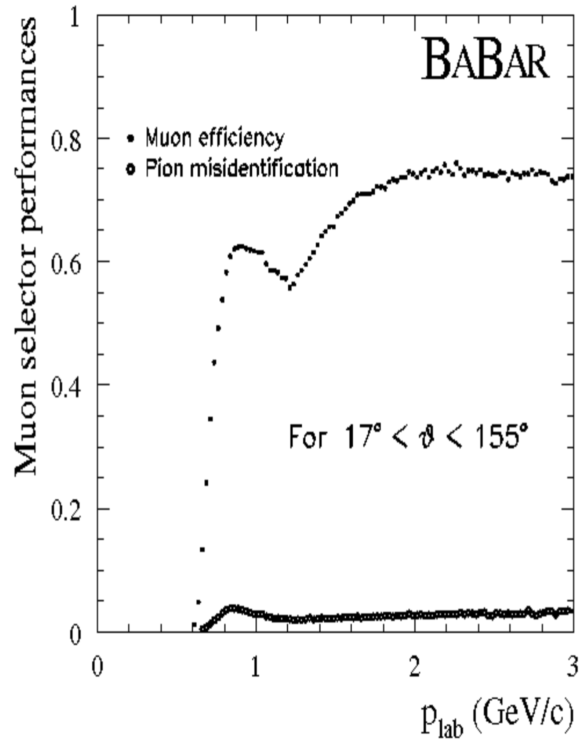
Kaons
- Efficiency: **70-90%**
- Pion misID: **1-7%**
- Momentum dependent

Electrons
- Efficiency: **90%**
- Pion misID**:<0.2%**

Muons
- Efficiency: **60-75%**
- Pion misID: **<3%**







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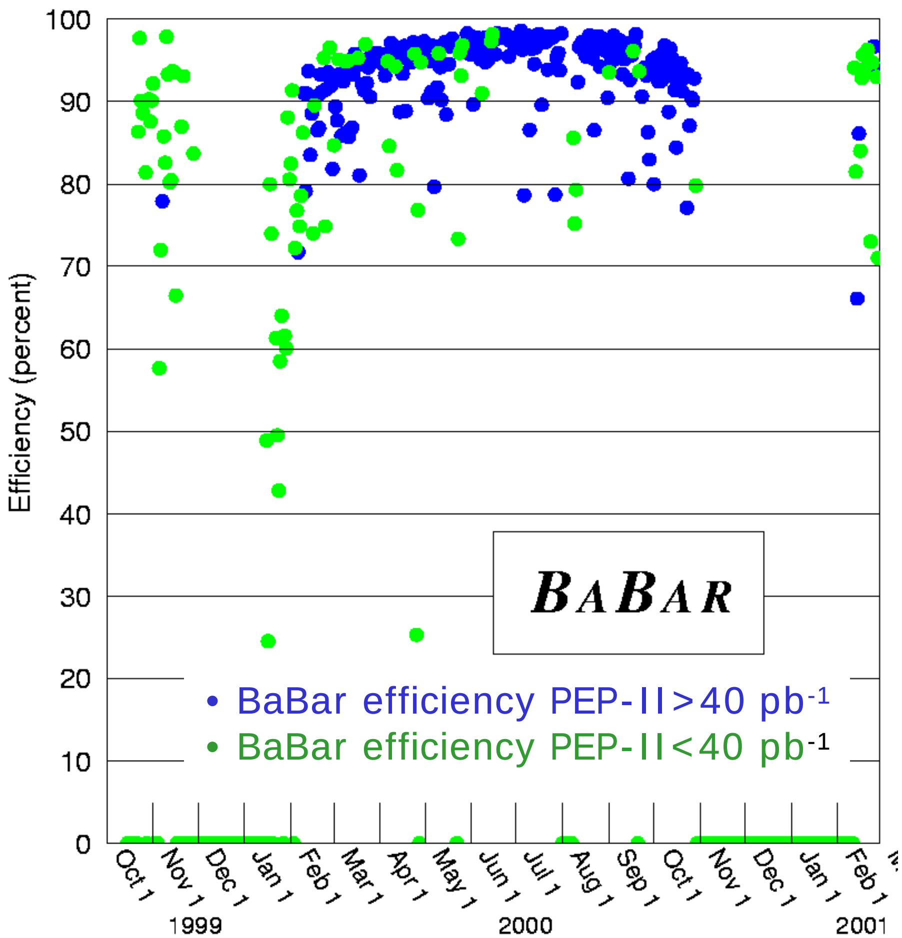
Online & offline event processing

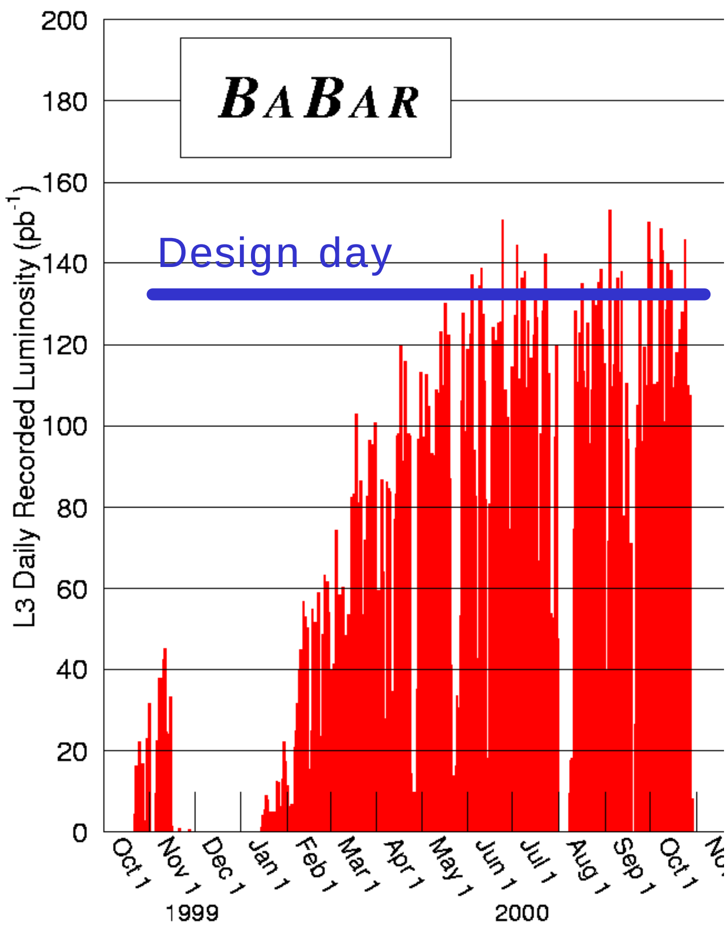
- Collision rate at interaction point: several MHz
- BaBar has a two level trigger system to select events of interest
  - Hardware implemented Level-1 trigger, output rate of ~2 kHz
  - Software implemented Level-3 trigger, output rate of ~100 Hz
  - Raw event size ~30 kB/event $\rightarrow$ write ~10Gb of data per hour
- Offline reconstruction of data follows with ~24 hours of data taking
  - Offline reconstruction performed in parallel by up to 250 SUN Workstations
    - In total about 1000 SUN workstations available for reconstruction, simulation and analysis
  - All data stored in Object Oriented database
    - Raw data and reconstruction level information on tape
    - Physics summary information on disk
  - Current database size ~ 300 Tb

Data taking efficiency

Efficiency by day



Daily integrated luminosity



(III) Sin2β and Mixing Analysis

sin2β and mixing analysis overview

Ia: Exclusive reconstruction of CP eigenstates (e.g. $B^0 \to J/\psi\ K_S$)

II: Tag initial flavour of $B^0_{CP/Mix}$ using tag of other B

sin2β $$A_{CP}(t) = \frac{\Gamma(B^0 \to f_{CP}, t) - \Gamma(\overline{B}^0 \to f_{CP}, t)}{\Gamma(B^0 \to f_{CP}, t) + \Gamma(\overline{B}^0 \to f_{CP}, t)} = A_{CP} \sin(\Delta m \cdot t)$$

mixing $$A_{Mix}(t) = \frac{\Gamma(B^0 \to f_{flav}, t) - \Gamma(\overline{B}^0 \to f_{flav}, t)}{\Gamma(B^0 \to f_{flav}, t) + \Gamma(\overline{B}^0 \to f_{flav}, t)} = A_{Mix} \cos(\Delta m \cdot t)$$

Ib: Exclusive reconstruction of flavour eigenstates

III: Precise measurement of time from $\Delta z \sim \beta\gamma c \Delta t$

Effect of experimental precision on CP measurement

- True δt,
  Perfect tagging

  $$F(\delta t) \propto e^{-|\delta t|/\tau}\,\{1 \pm \sin 2\beta \cdot \sin \Delta m\ \delta t\}$$

- True δt,
  imperfect tagging

  $$F(\delta t) \propto e^{-|\delta t|/\tau}\,\{1 \pm D\ \sin 2\beta \cdot \sin \Delta m\ \delta t\}$$

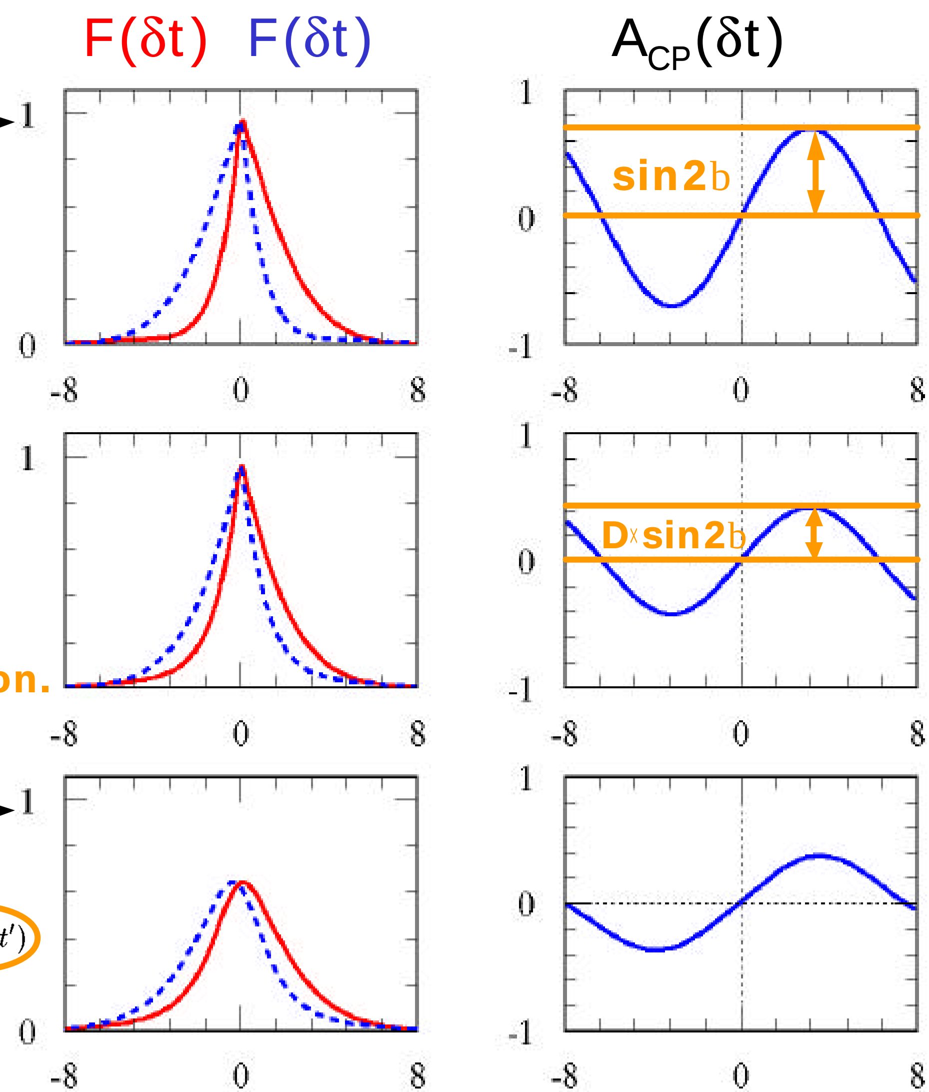
  D = (1-2ω) where w is mistag fraction.

  Must measure flavor tag Dilution.

- Measured δt,
  imperfect tagging

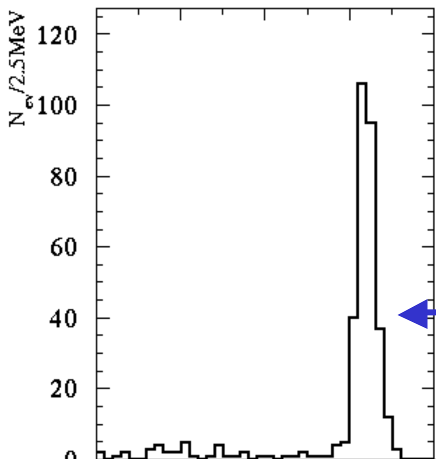
  $$F(\delta t') \propto e^{-|\delta t|/\tau}\,\{1 \pm D \cdot \sin 2\beta \cdot \sin \Delta m\ \delta t\} \otimes R(\delta t, \delta t')$$

  Must measure dt resolution properties.



Ia: Golden Modes: $J/\psi\ K_S\ (\rightarrow\pi^+\pi^-, \pi^0\pi^0)$, $\psi(2s)\ K_S(\rightarrow\pi^+\pi^-)$

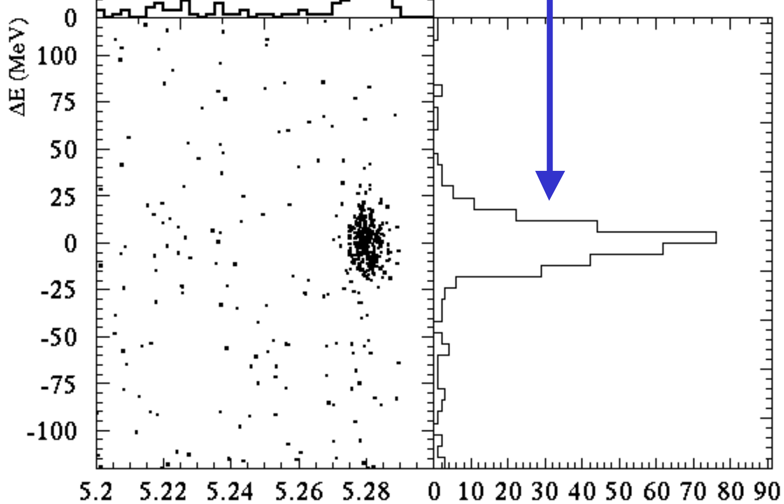
- Reconstruct 2 independent kinematic variables for each reconstructed B candidate



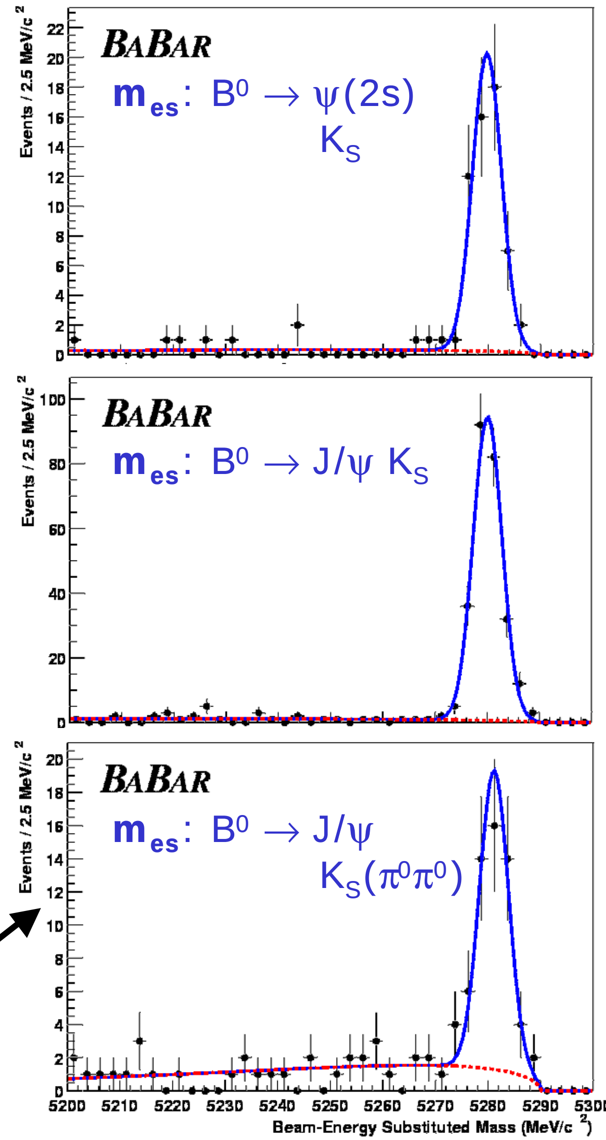
Exploit beam energy constraints to enhance resolution

$$m_{es} = \sqrt{E^{*2}_{\text{beam}} - \sum \vec{p^*}_i}$$

$$\Delta E = E^*_B - E^*_{\text{beam}}$$



3σ cut on ΔE applied



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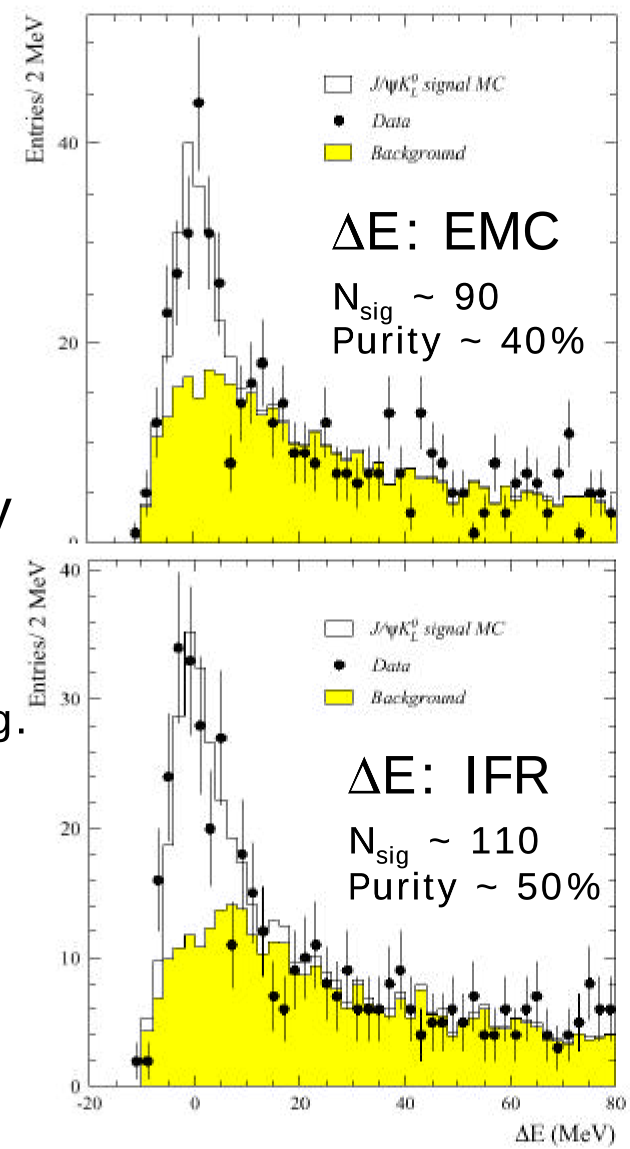
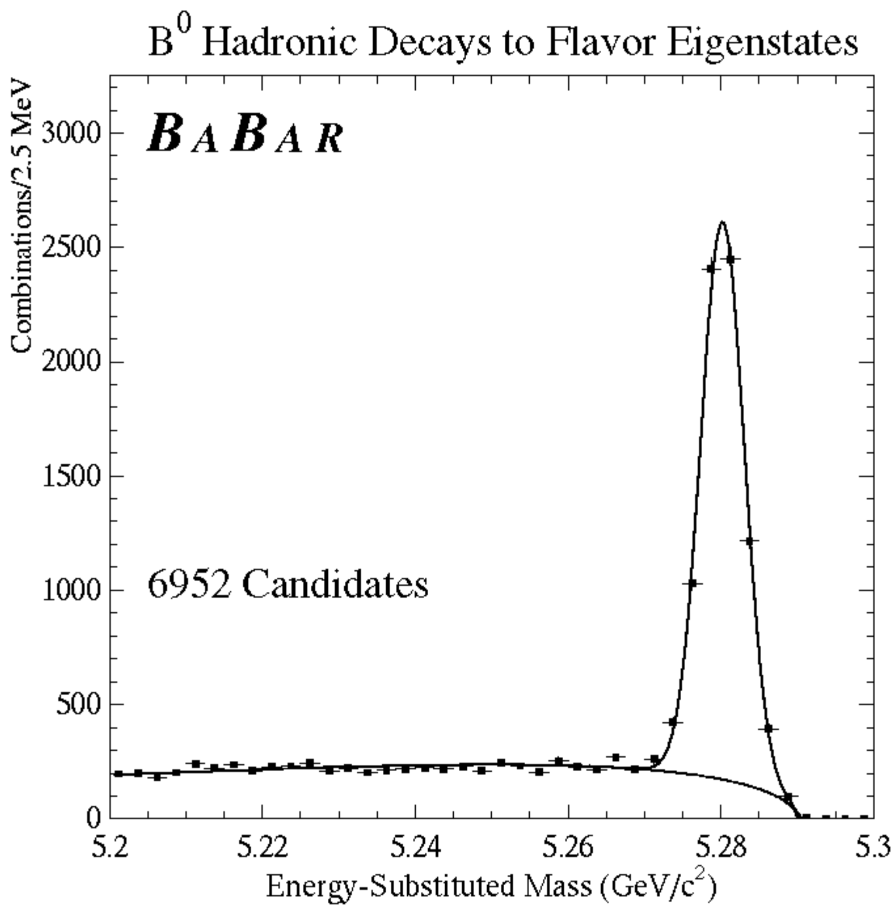
Ib: The $J/\psi\ K_L$ CP Mode

- $J/\psi\ K_L$ has opposite CP of $J/\psi\ K_S$, same branching ratio
- K_L identification challenging
  - No positive detector signature, KL ID assigned by eliminating other hypotheses
- Only direction measured, not energy
  - Calculate K_L energy from kinematics, using $mB_{es} = mB_{PDG}$
  - Can no longer use cut on m_B to reject bkg.
- Substantial background
  - Most background (~70%) has real K_L, from modes like $J/\psi\ K^{*\pm 0}$ ($\rightarrow K_L\ \pi^{\pm 0}$)
  - Background is not CP-neutral. Determine effective CP eigenvalue from MC



Ib: The B^0 flavour eigenstate sample

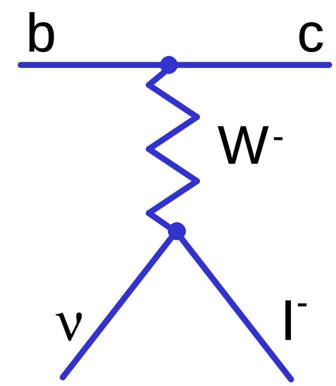
- Reconstructed modes
  - $B^0 \to D^{(*)-} \pi^+$
  - $B^0 \to D^{(*)-} \rho^+$
  - $B^0 \to D^{(*)-} a_1^+$
  - $B^0 \to J/\psi\ K^{*0}\ (K^+\pi^-)$
  - $B^+ \to D^{(*)0} \pi^+$
  - $B^+ \to J/\psi\ K^+$
  - $B^+ \to \psi(2s)\ K^+$
- High statistics
  - **6952 B^0 (90% purity)**
  - 7645 B^+ (93% purity)
  - **10x CP sample**



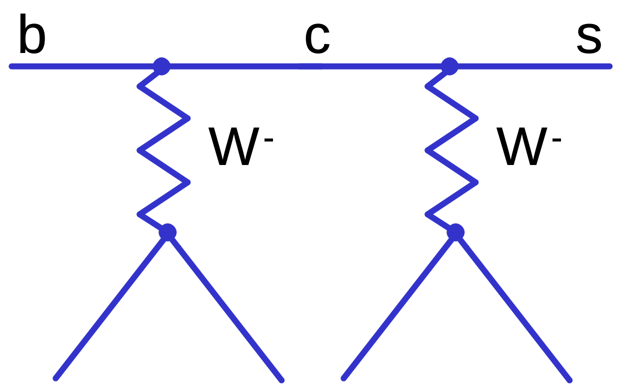
II: Tag initial flavour of $B^0_{CP/Mix}$

- Determine from flavour of other B in the event
  - 4 Mutually exclusive hierarchical categories

- **Lepton tag**: $b \to l^-$, $\bar{b} \to l^+$
  - Select leptons from $b \to c\, l\, \nu$ decay
  - Reject $c \to s\, l\, \nu$ by requiring $p^*(l) > 1.\mathrm{GeV}$
  - Low efficiency, low mistag fraction

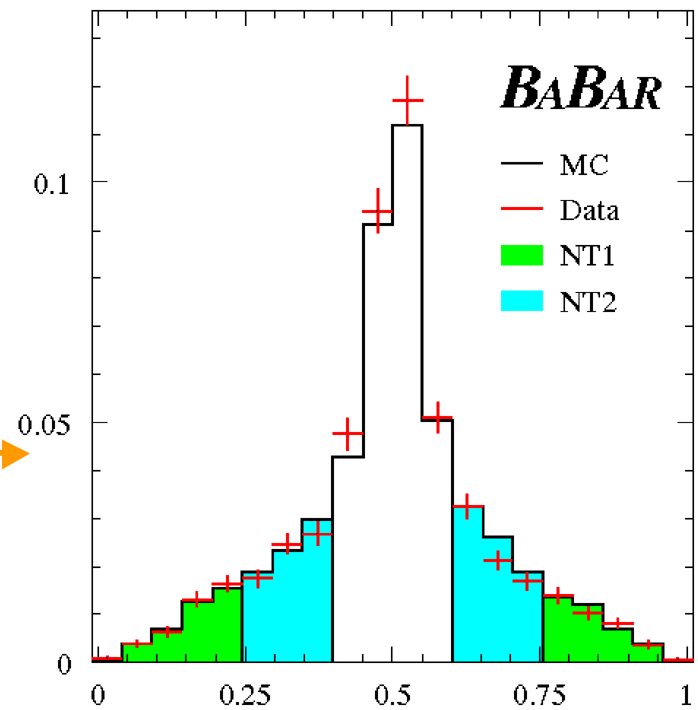


- **Kaon tag**: $b \to K^-$, $\bar{b} \to K^+$
  - Good Kaon particle ID essential
  - Tagged flavour determined by total charge of identified K



II: Tag initial flavour of $B^0_{CP/Mix}$, using tag of the other B

- Neural Net tag(2):
  - Sub networks identify
    - Leptons (primary and secondary)
    - Kaon, Slow pions from D*+ decay.
  - Networks combined along with addition event shape variables
  - Network output is continuous variable [0,1]
  - Output binned in **NT1**,**NT2**, no tag
  - Average mistag rate/efficiency measured for each bin.



Effect of imperfect flavour tagging

- Affects value and precision of sin2β measurement:

Dilution factor

Mistag fraction

Value

$$A_{CP} \propto D = (1-2w)$$

Precision

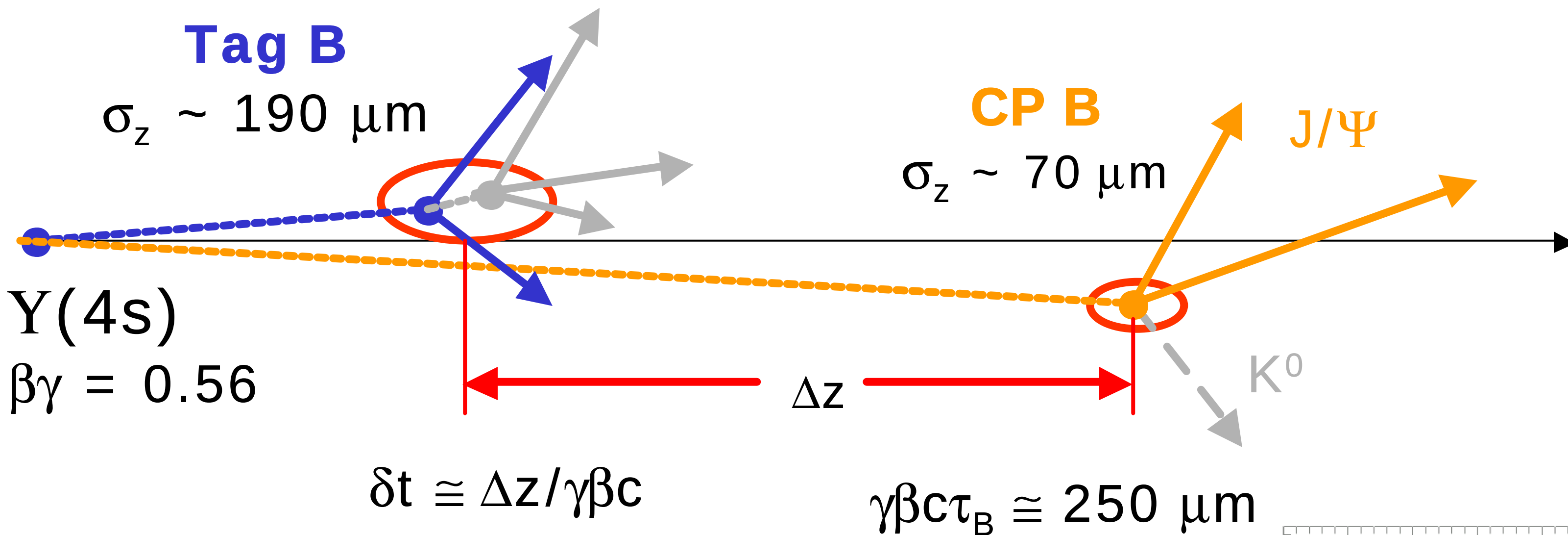
$$s^{stat}(A_{CP}) \propto \frac{1}{\sqrt{Q}}$$

Effective tagging efficiency

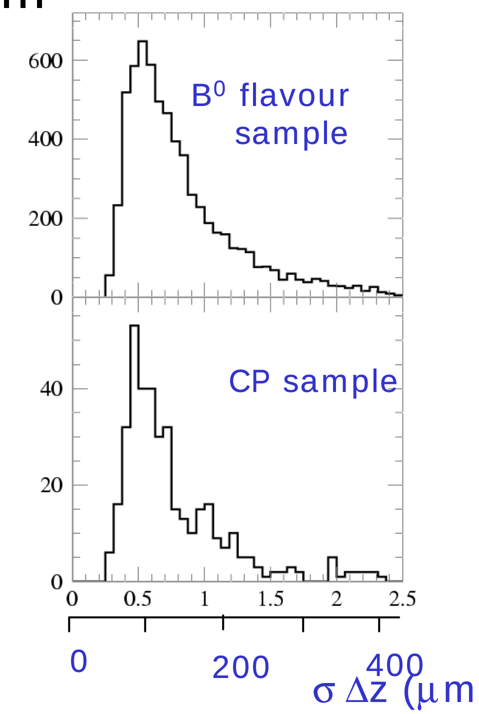
$$Q = e^{tag} D^2 = e^{tag}(1-2w)^2$$

Tagging efficiency

III: Precise measurement of time δt

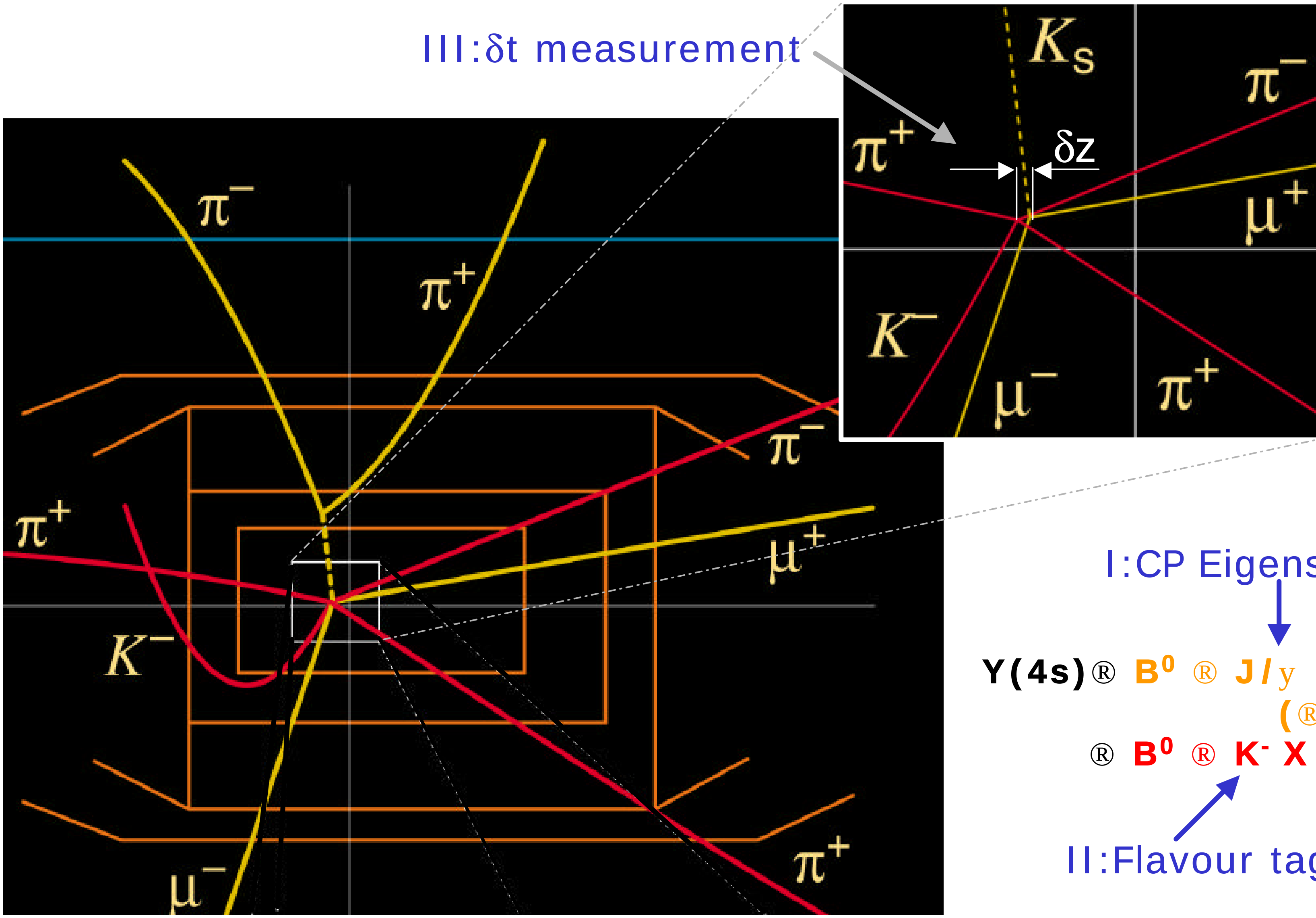


- $J/\psi \rightarrow l^+l^-$ dominates in determination of CP vertex.
- Tracks not from CP B combined to form tag vertex.
    - Tracks with large χ^2 iteratively removed.
    - Long-lived particles (K_S , Λ) explicitly reconstructed.
    - Photon conversions ($\gamma \rightarrow e^+e^-$) removed.
- Efficiency for CP sample 86 %.



Event display of golden event

III:δt measurement



I:CP Eigenstate

$\Upsilon(4s) \rightarrow B^0 \rightarrow J/\psi\ K_S$
$(\rightarrow \pi^+\pi^-)$
$\rightarrow B^0 \rightarrow K^-\ X$

II:Flavour tag

Breakdown of CP events

Tag	CP =1 modes			$J/\psi K^0_L$			Total		
	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot
$e+K$	3	0	3	1	6	7	4	6	10
$\mu+K$	3	1	4	3	5	8	6	6	12
e	7	8	15	11	8	19	18	16	34
μ	5	7	12	5	6	11	10	13	23
Lepton	18	16	34	20	25	45	38	41	79
Kaon	80	76	156	70	60	130	150	136	286
NT1	13	15	28	16	6	22	29	21	50
NT2	30	25	55	32	27	59	62	52	114
Total tag	141	132	$\boxed{273}$	138	118	$\boxed{256}$	279	250	$\boxed{529}$
No tag	109			130			239		
Tag ε (%)	71±2			66±2			69±2		

Fit strategy

- Global unbinned maximum likelihood fit
  - **Mixing : B0 flavour eigenstate sample**
  - **sin2b : CP & flavour eigenstate sample**

High statistics flavour sample will constrain most dilution and resolution parameters

- Parameters modeling mistag, Δt resolution and background are floated to obtain an empirical description of these properties from data

Floating all parameters simultaneously gives correct propagation of errors and correlations

Parameter	#params	Driving subsample
sin2β	1	CP
Δm_d	1	Flavour
D & ΔD	4x2 = 8	Flavour
Signal Δt resolution	4+5=9	Flavour & CP
Bkg. Composition	4+2=6	mB sideband
Bkg. D	4x2 = 8	mB sideband
Bkg. Δt resolution	3	mB sideband

Only in CP fit

Only in Mixing fit

Largest correlation with sin2β: 7.6%

35 floating parameters in total

Blind Analysis strategy

- The sin2β and mixing results are blinded while the analysis is in progress

  - sin2β is hidden by adding an arbitrary offset and an arbitrary sign flip

  - Δt is hidden by multiplying Δt by the sign of the flavour tag and adding an arbitrary offset

  – The blinded approach allows systematic studies of tagging, vertex resolution and their correlations to be done while keeping the value of sin2β hidden

  – The result was unblinded two weeks before publication

Fit results: the δt resolution model

Parameterization: Sum of 3 Gaussians:

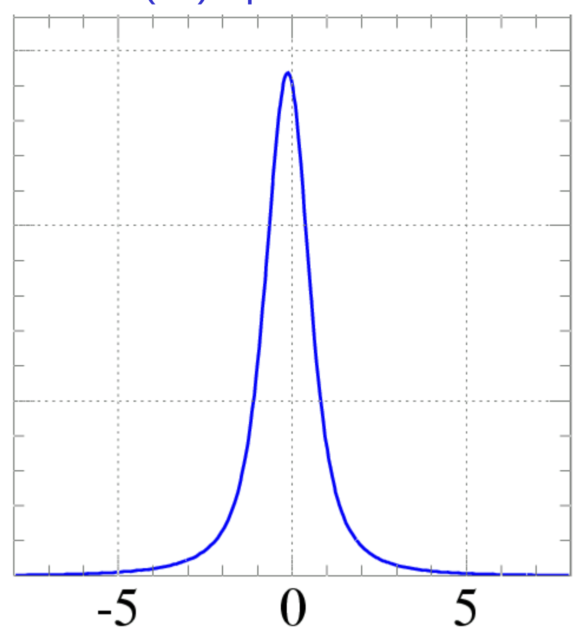
$$\begin{aligned} R(\delta t, \delta t') &= f_c \cdot G_c\,(\delta t' - \delta t,\ \sigma_c,\ \mu_{c,i}) \quad \text{Core} \\ &+ f_t \cdot G_t\,(\delta t' - \delta t,\ \sigma_t,\ \mu_t) \quad \text{Tail} \\ &+ f_o \cdot G_o\,(\delta t' - \delta t,\ \sigma_o = 8\text{ ps},\ \mu_0 = 0) \quad \text{Outlier} \end{aligned}$$

Parameter	Value
S_{Core}	1.1 ± 0.1
S_{Tail}	3.8 ± 0.9
f_{Tail} (%)	11 ± 5
f_{Outlier} (%)	0.8 ± 0.5
$\delta_{\text{Core,}\mathtt{Lepton}}$ (ps)	0.08 ± 0.10
$\delta_{\text{Core,}\mathtt{Kaon}}$ (ps)	-0.21 ± 0.05
$\delta_{\text{Core,}\mathtt{NT1}}$ (ps)	0.01 ± 0.10
$\delta_{\text{Core,}\mathtt{NT2}}$ (ps)	-0.18 ± 0.09
δ_{Tail} (ps)	-0.46 ± 0.38

width: $\sigma_{evt} \times S_{fit}$

Bias parameters

δt residual distribution from fit:
Projection resolution function over σ(dt) spectrum in data



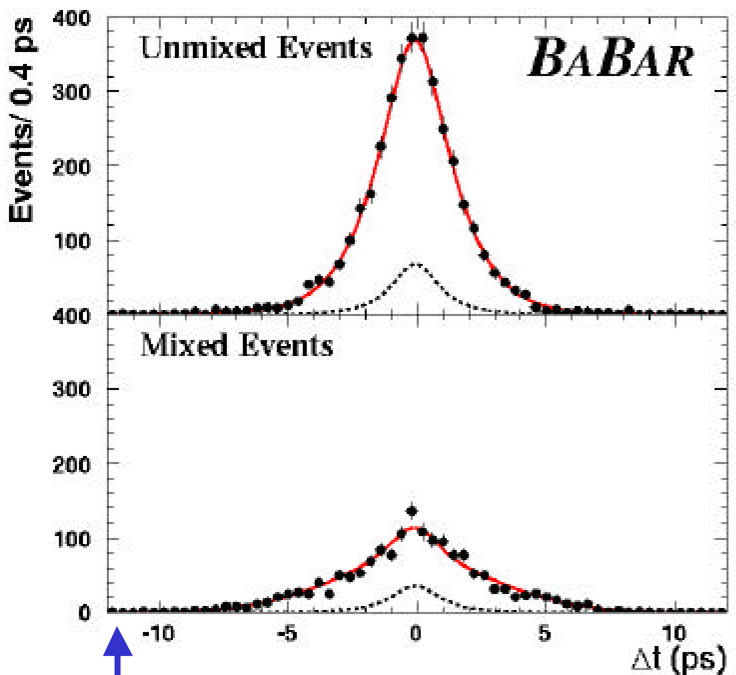
Fit results: mistag rates

- Mistag rate information mainly carried by B^0 flavour sample, but is also valid for B^0 CP sample
  - Lepton tag has the lowest mistag rate / highest dilution
  - Kaon tag has the highest tagging power

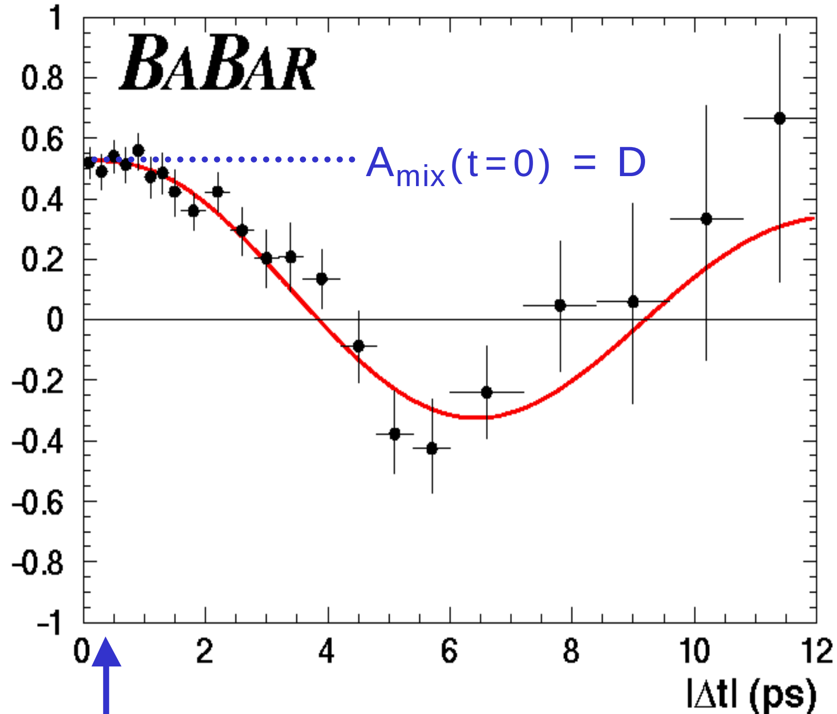
Flavor tag	Efficiency	Dilution	$Q=\varepsilon D^2$
Lepton	10.9 ± 0.4 %	77 ± 4 %	6.4 ± 0.7 %
Kaon	36.5 ± 0.7 %	66 ± 3 %	15.8 ± 1.3 %
NT1	7.7 ± 0.4 %	58 ± 6 %	2.6 ± 0.5 %
NT2	13.7 ± 0.5 %	37 ± 5 %	1.8 ± 0.5 %
Total	68.9 ± 1.0 %		**26.7 ± 1.6 %**

$\boxed{\text{Error on } \sin 2\beta \propto 1/\sqrt{(Q)}}$

Fit results: Δm_d from mixing fit



Fitted Δt distribution of events tagged as mixed or unmixed



$$A_{Mix}(t) = \frac{\Gamma(B^0 \to f_{flav}, t) - \Gamma(\overline{B}^0 \to f_{flav}, t)}{\Gamma(B^0 \to f_{flav}, t) + \Gamma(\overline{B}^0 \to f_{flav}, t)}$$

Preliminary result: Dm$_d$ = 0.519 ± 0.020 ± 0.016 ps^{-1}

? m$_d$(PDG) = 0.472 ± 0.017 ps^{-1}

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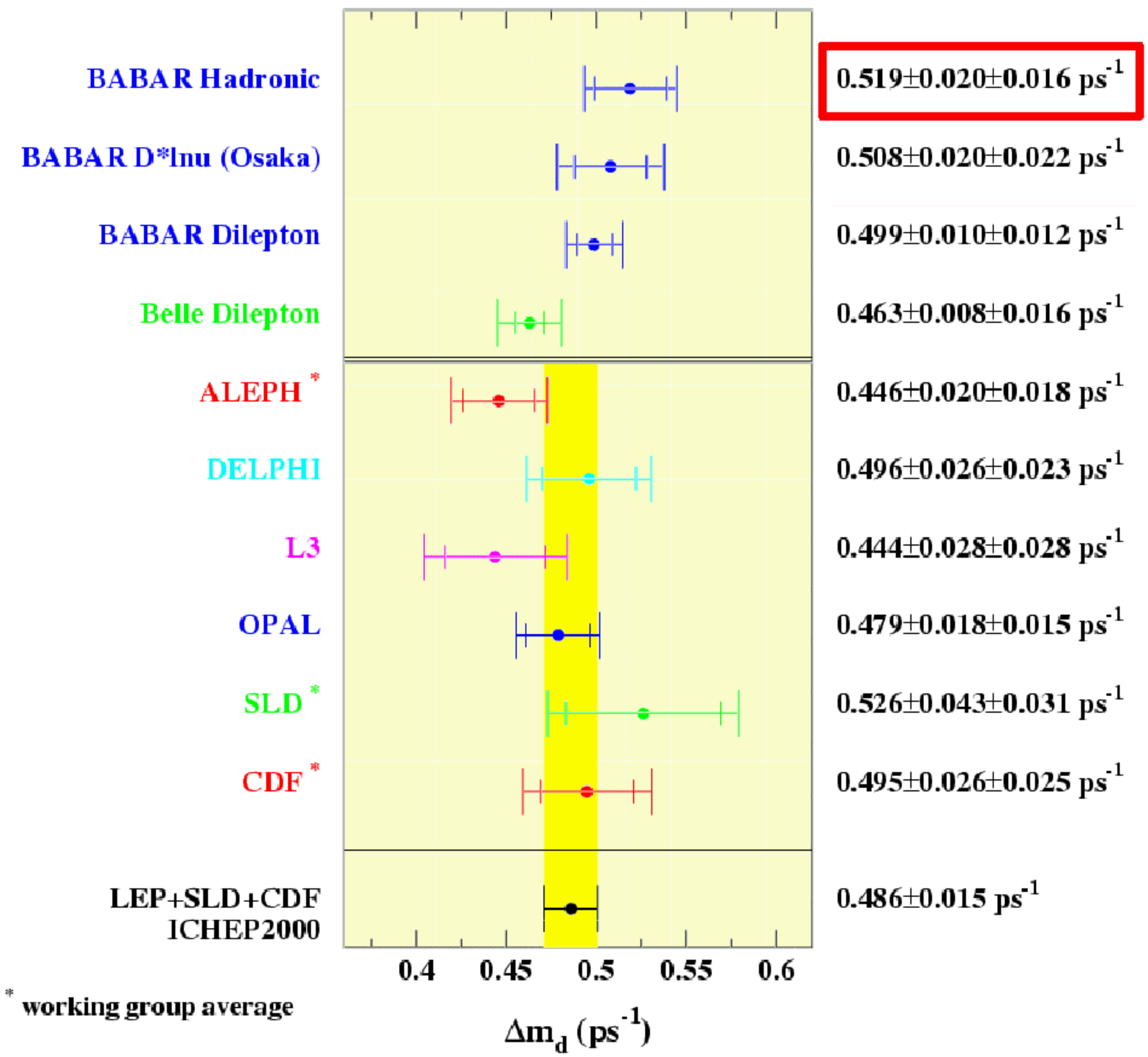
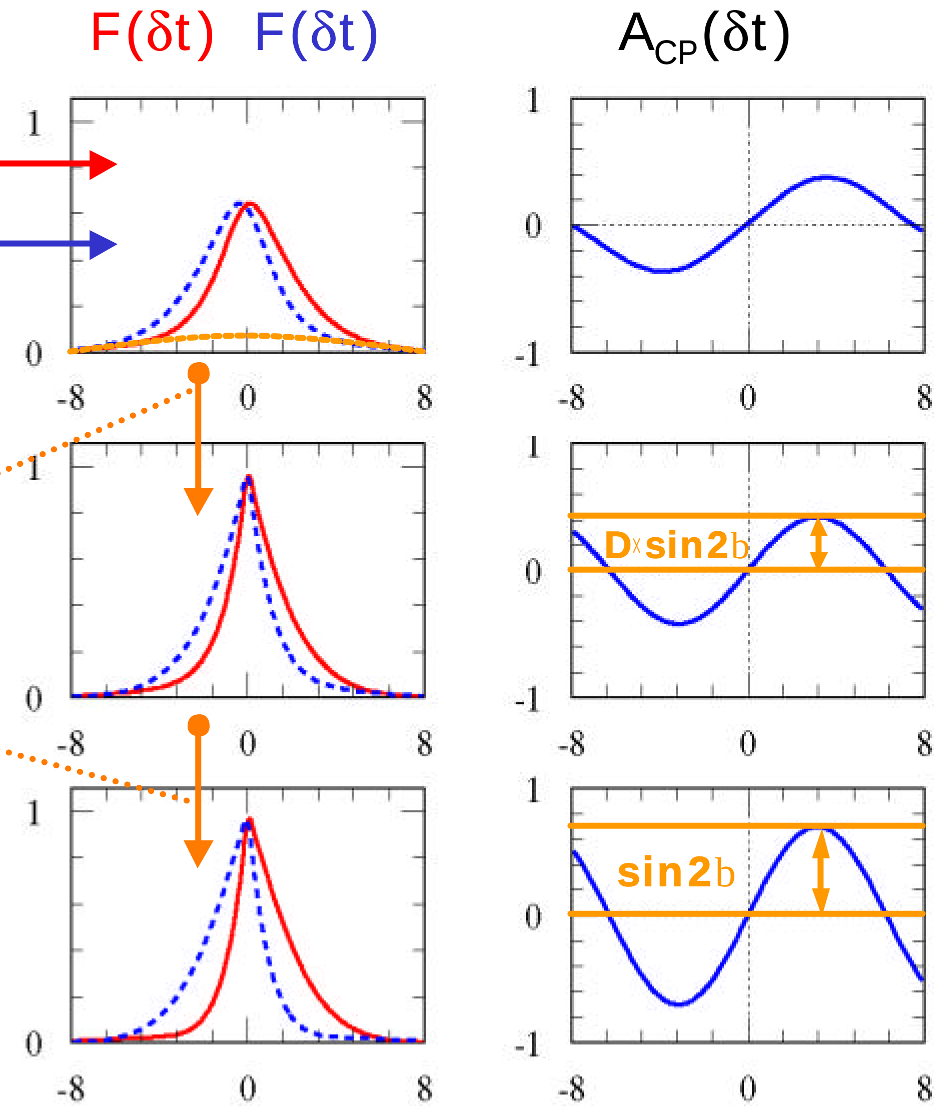
Comparison of Δm_d results



Guide to sin2β fit results

- Input consists of
  - δt distribution for B^0 tags
  - δt distribution for $\overline{B^0}$ tags
- Fit model accounts for
  - Backgrounds
  - δt resolution
  - Dilution
- CP=+1/-1 modes fitted with separate PDFs
  - CPV moves flavour tagged δt distributions in opposite directions
  - Different backgrounds

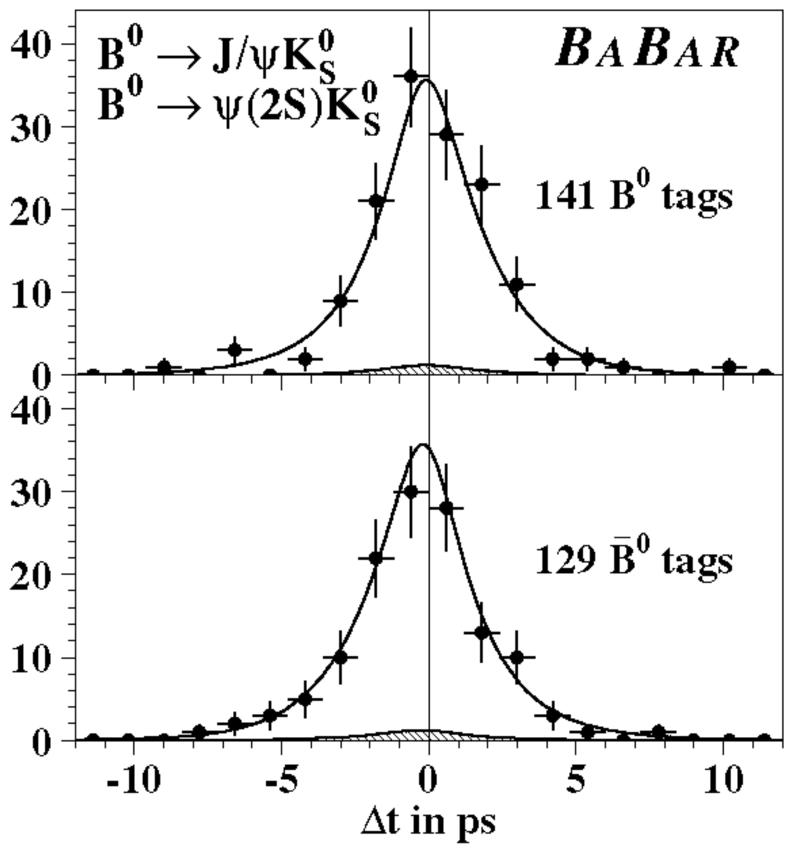


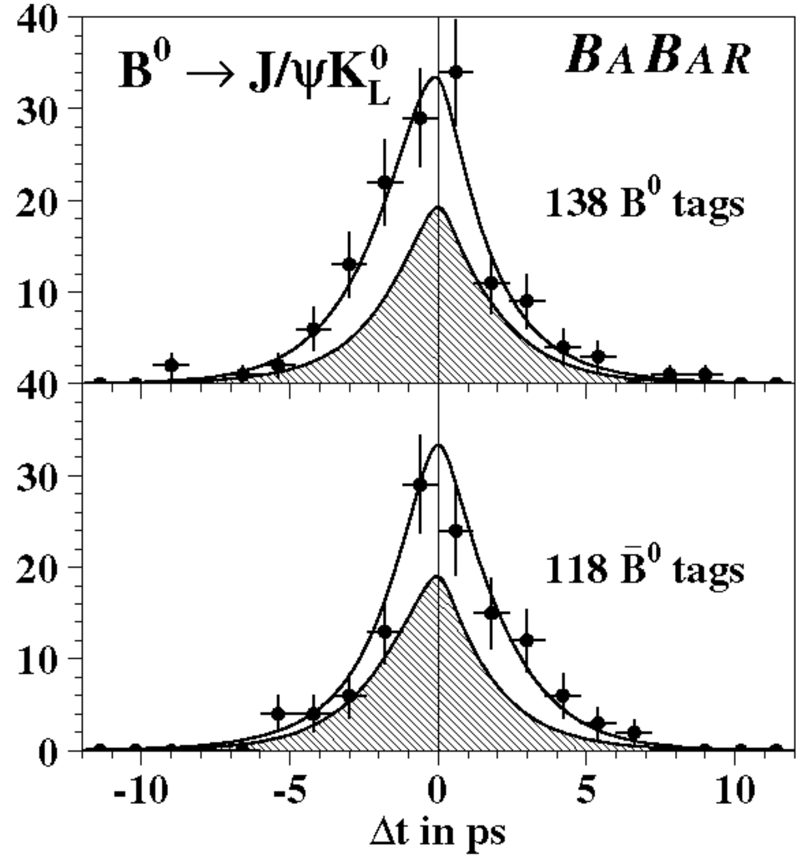
Fit results: δt distributions of $\sin 2\beta$ fit by flavour tag

Combined:
$\sin 2\beta = 0.34 \pm 0.20 \pm 0.05$

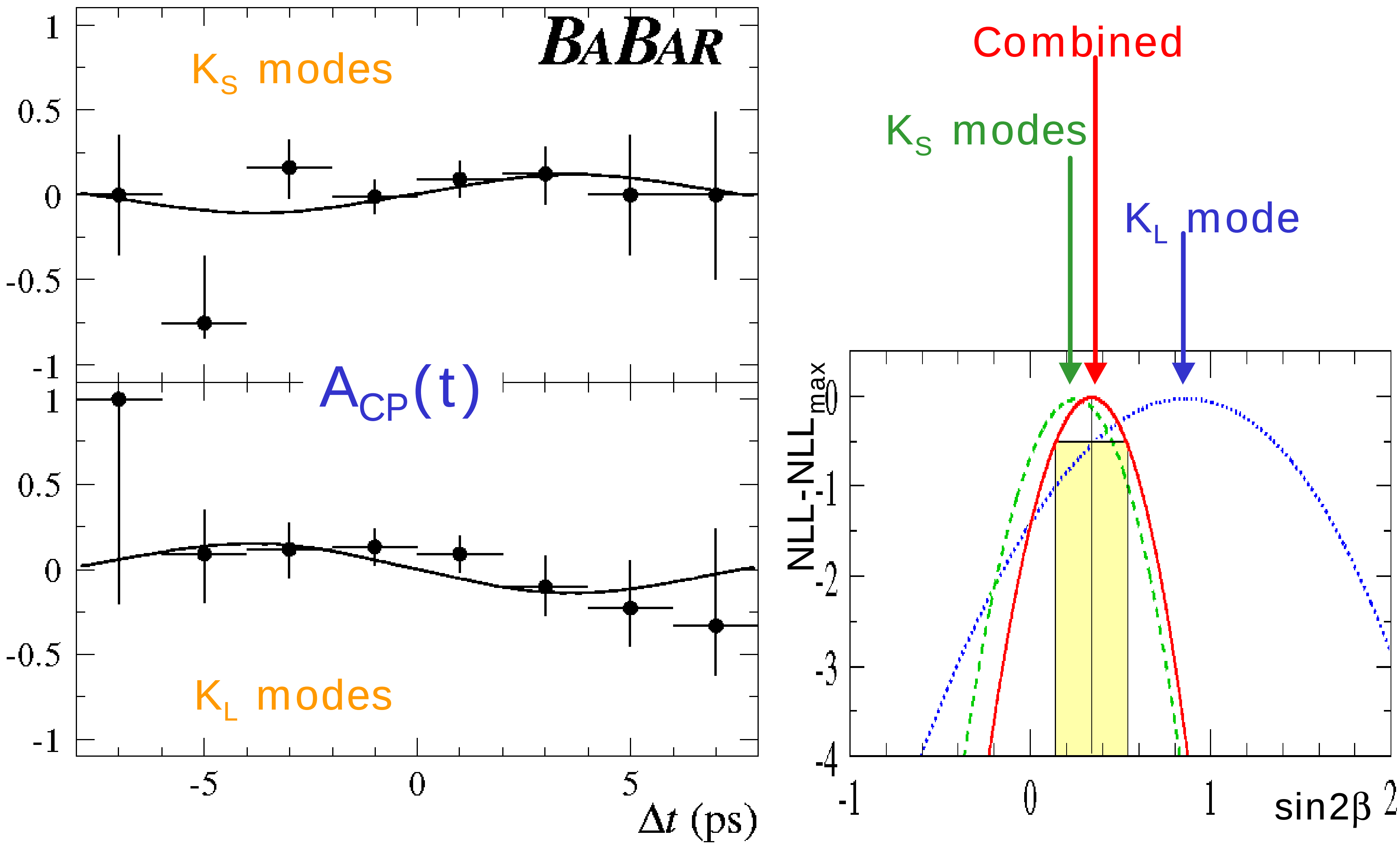
K_s modes:
$\sin 2\beta = 0.25 \pm 0.22 \pm 0.05$

K_L mode:
$\sin 2\beta = 0.87 \pm 0.51 \pm 0.14$





sin2β fit: Raw $A_{CP}(t)$ and likelihood scan



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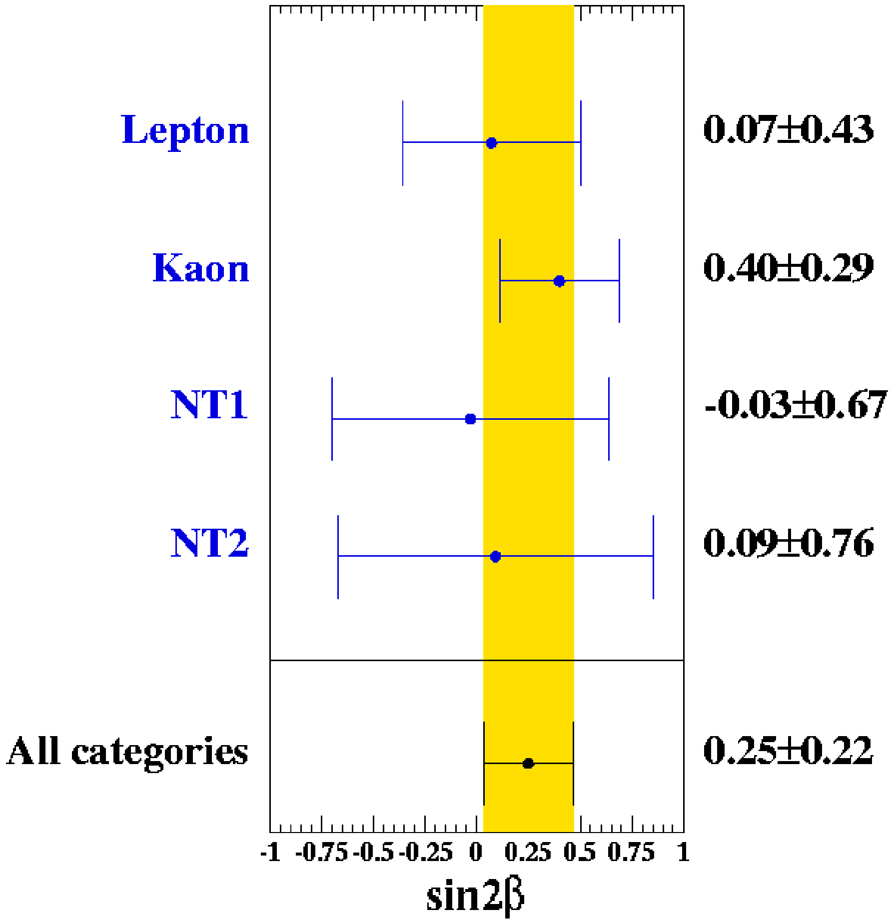
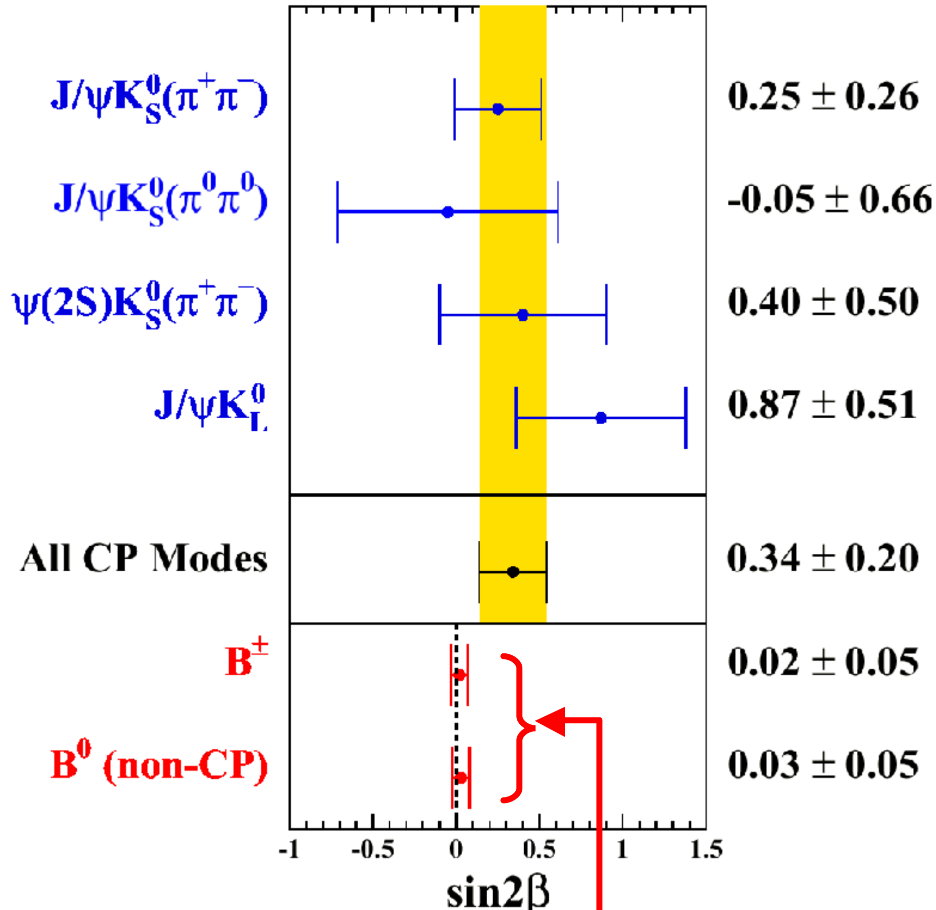
Fit sanity checks: Breakdown by reconstruction/tagging mode





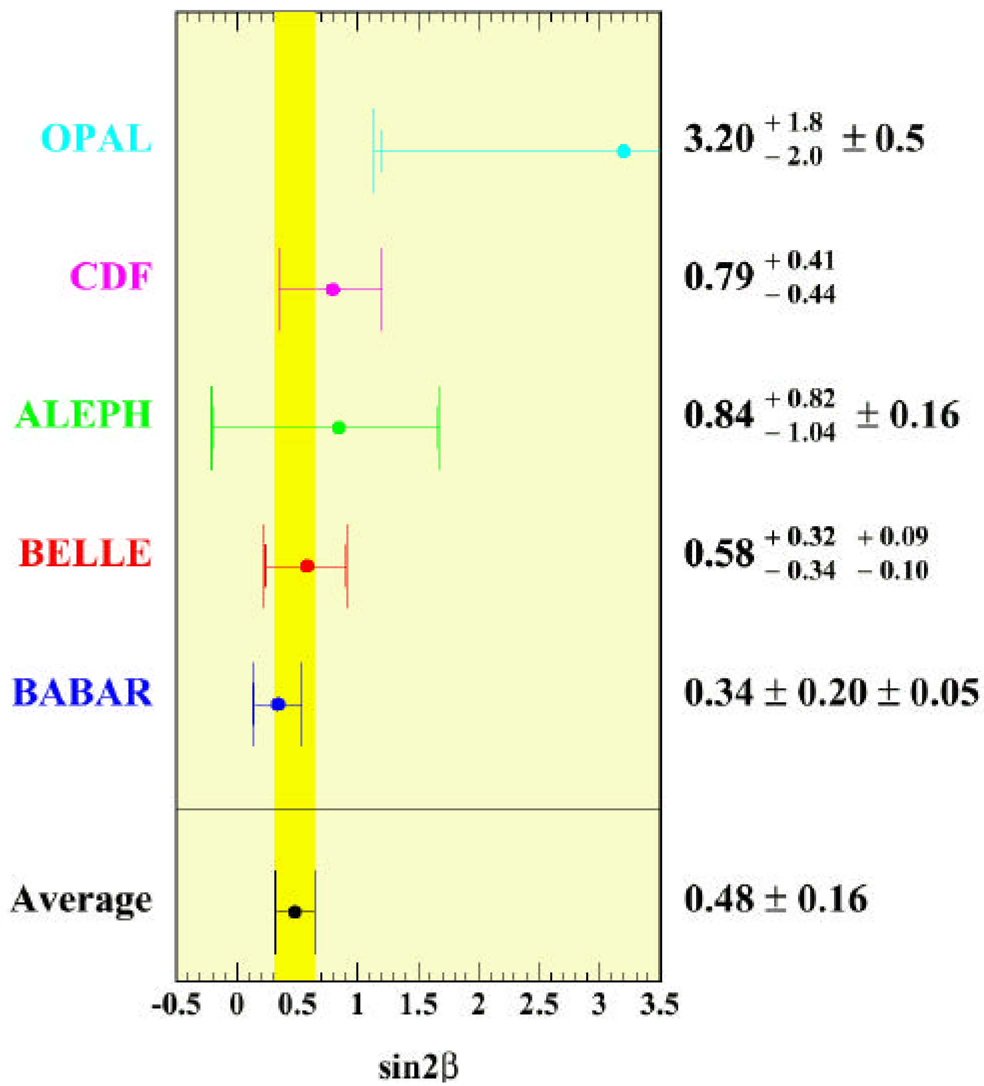
Control samples: expect sin2β=0

Fit results: systematic errors

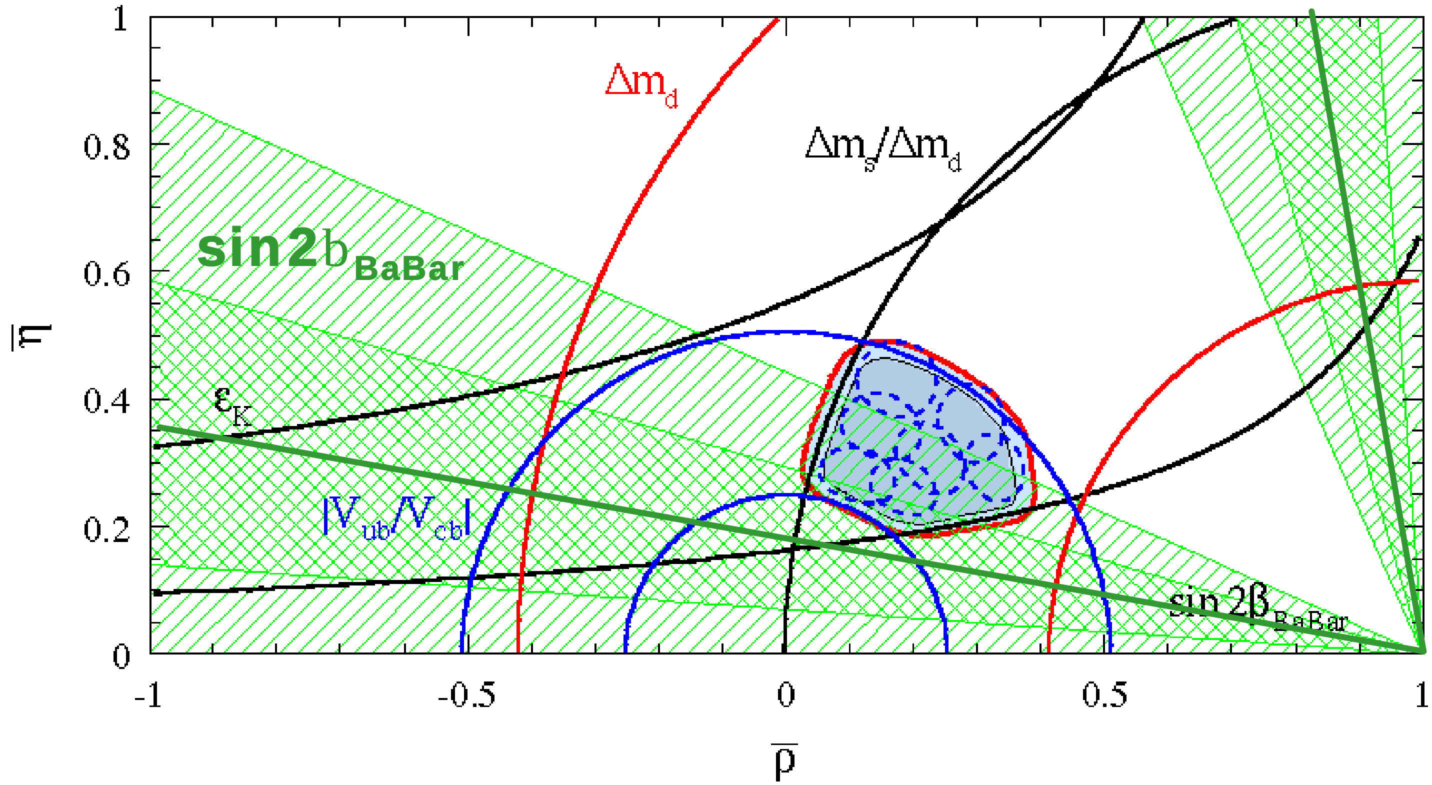
- Dominant systematic:
  residual Drift Chamber & Silicon tracker misalignment
  (δt determination)
- Many systematic error contributions will reduce with increasing statistics
- Measurement is (and will be for a long time) statistics limited

Source	K_S	K_L	Combined
δt determination	0.04	0.04	0.04
K_s modes BG	0.02		0.02
K_L BG J/Ψ br. fr.		0.05	<0.01
K_L BG CP (non-Ψ, jumble, K*)		0.06	0.01
K_L Signal fraction		0.10	0.01
B lifetime	0.01	<0.01	<0.01
Δm	0.01	0.01	0.01
Other	0.01	0.04	0.01
Total	**0.05**	**0.14**	**0.05**

Comparison with existing sin2β measurements



BaBar sin2β and the Unitarity Triangle



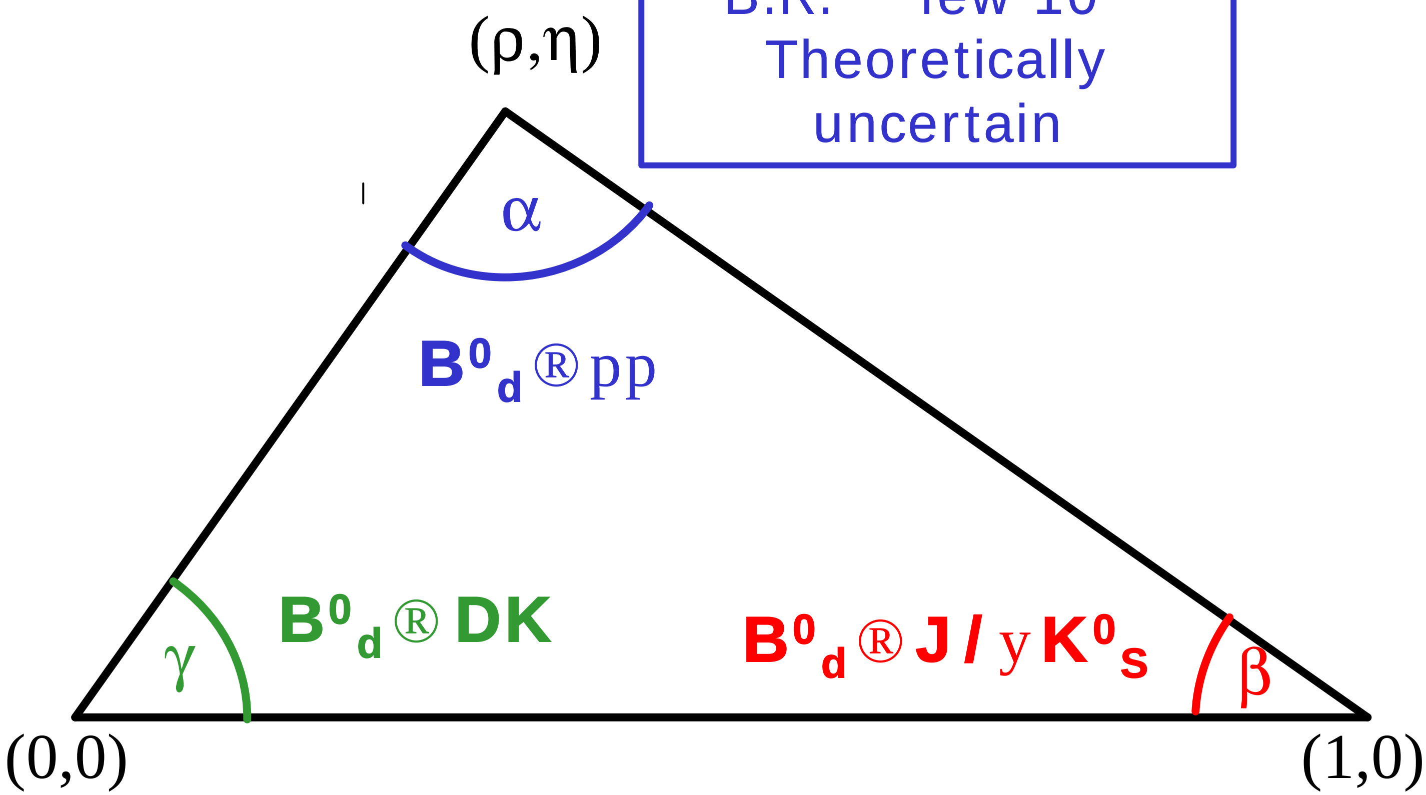
BaBar sin2β not used in CKM fit

- ε_K : CP violation in K^0-K^0 system
  - Box diagrams with t and c quarks
- Δm_d: B^0 mixing
  - $\Delta m_d \propto |V_{td}V^*_{tb}|^2$
- $|V_{ub}/V_{cd}|$: V_{ub} charmless semileptonic B decay
  - Lepton p* endpoint spectrum
- $\Delta m_s/\Delta m_d$: B_s and B_d mixing
  - Lattice QCD systematics cancel in ratio

(IV) Outlook & Summary

What's next...

B.R. ~ few 10^{-6}
Theoretically
uncertain

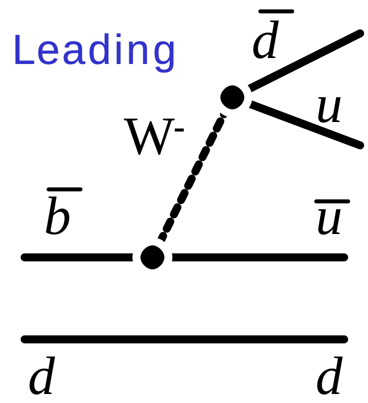


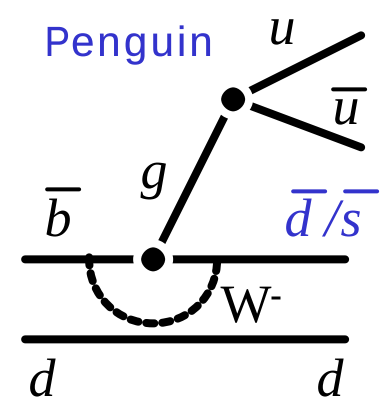
Eff. B.R ~10^{-7}, tough!!

Very clean,
Eff B.R. ~ 10^{-4}

Charmless 2-body decays: road to sin2α

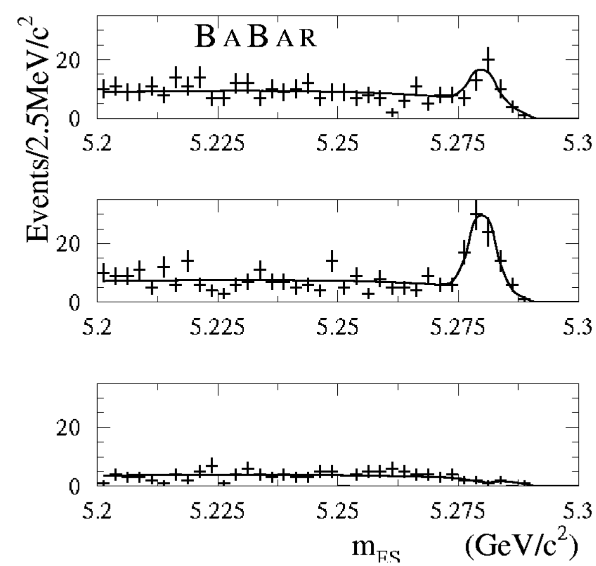
- Decay $B^0 \rightarrow \pi^+\pi^-$ sensitive to sin2α
  - Theoretically less clean, penguins have different weak phase





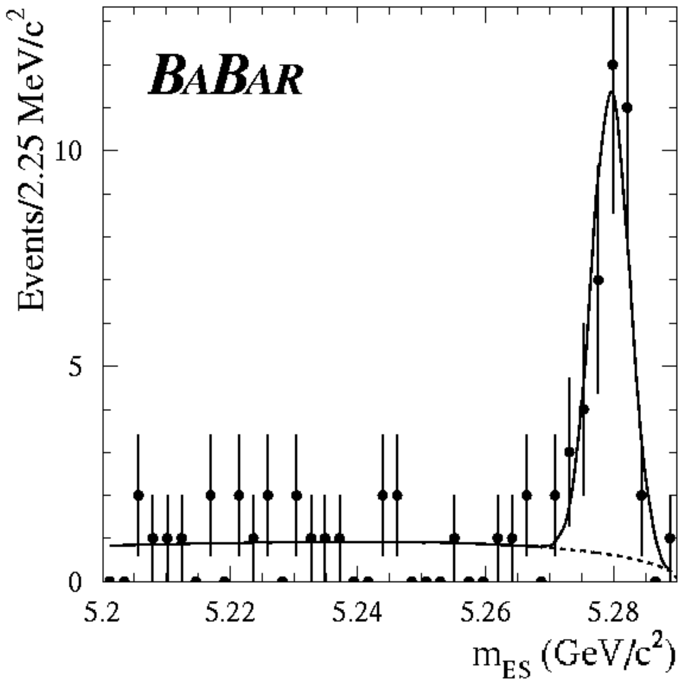
- B $\rightarrow$ $h^+h'^-$ analysis with likelihood fit for amount of $\pi\pi$,πK,KK
  - ✓ Large B$\rightarrow$ $K^+\pi^-$ br. fraction indicates non-negligible penguin contribution

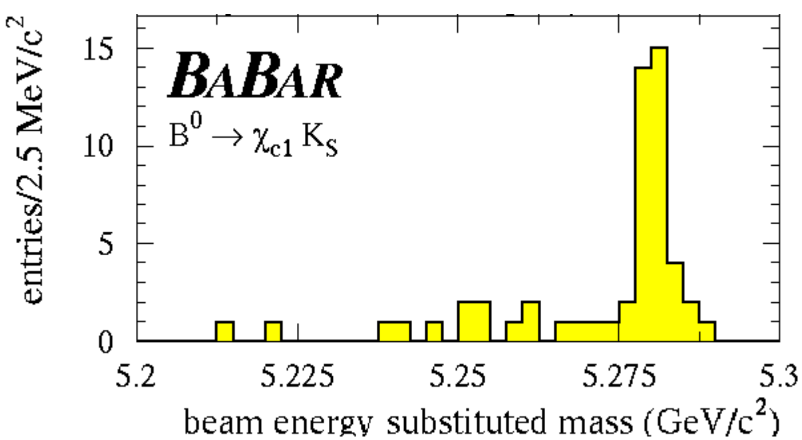
Mode	Yield	BR x 10^6
$\pi^+\pi^-$	41 ± 10	$4.1 \pm 1.0 \pm 0.7$
$K^+\pi^-$	169 ± 17	$16.7 \pm 1.6 \pm ^{1.2}_{1.7}$
K^+K^-	$8.2 \pm ^{7.8}_{6.1}$	<2.5

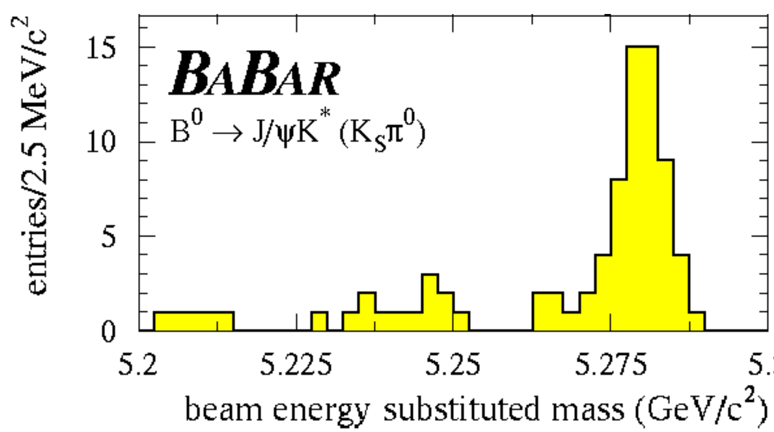


Additional CP modes for sin2β

- More CP modes in preparation for sin2β analysis
  - $B^0 \rightarrow D^* D^*$
  - $B^0 \rightarrow J/\psi K^{*0} (K_S \pi^0)$
  - $B^0 \rightarrow \chi_{c1} K_S$
  - Other modes in progress

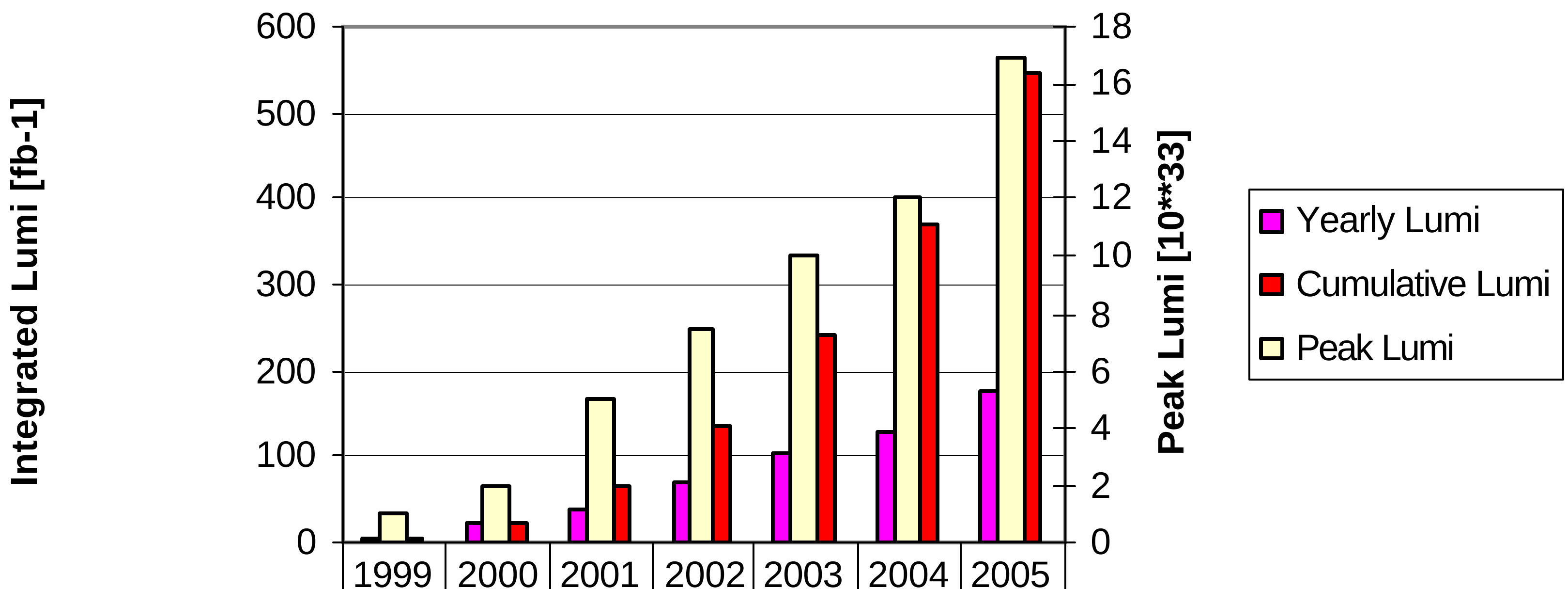






Luminosity

- More data on the way
  - Expect >25fb-1 more by end of August



	1999	2000	2001	2002	2003	2004	2005
Yearly Lumi	2	23	40	70	105	130	175
Cumulative Lumi	2	25	65	135	240	370	545
Peak Lumi	1	2	5	7.5	10	12	17

Year

Summary

- PEP-II and BaBar are operating at or above design after only one year.

- Most precise sin2β measurement to date:
  sin2b = 0.34 ± 0.20 (stat) ± 0.05 (syst)

- Competitive mixing results:
  Dm_d = 0.519 ± 0.020 ± 0.016 ps^{-1} (hadronic)

- Mode CP modes in preparations for sin2β, many other analyses in progress.

- The 2001 run is well underway
  - expect ~500fb^{-1} by 2005