CP Violation and Flavour

Lecture 4

Dottorato in Fisica – XX Ciclo

Livio Lanceri
Università di Trieste
and INFN

Recap of Lecture 3 and Outline

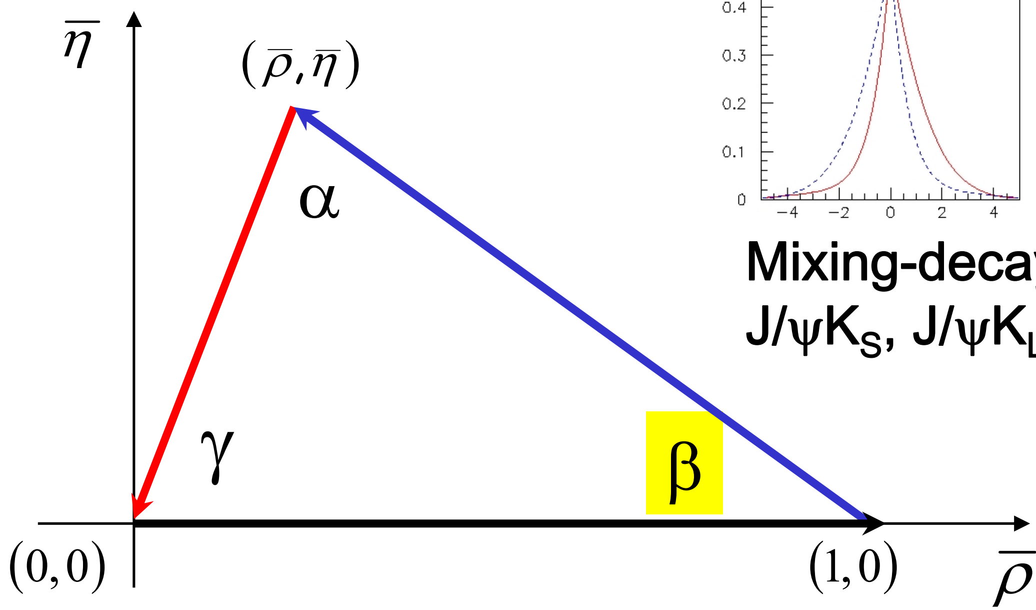
- B_s mixing from CDF and D0: still not seen
- "Direct" CPV seen in $B_d \to K\pi$
- "Indirect" CPV in mixing (ASL) not seen yet

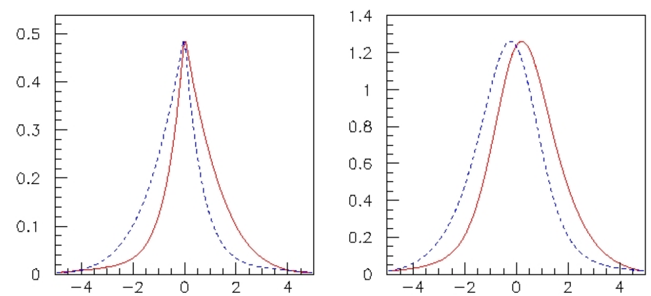
Now… Unitarity Angles!

- sin2β (sin2ϕ_1)
  - $b \to c\bar{c}s$ and $b \to s\bar{s}s$

- Methods
- Results
- Statistics, systematics

sin2β (ϕ_1): time-dependent CP asymmetries in $b \to c\bar{c}s$



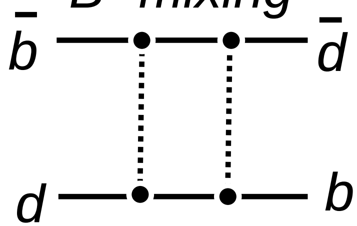


Mixing-decay interference

$J/\psi K_S$, $J/\psi K_L$, …

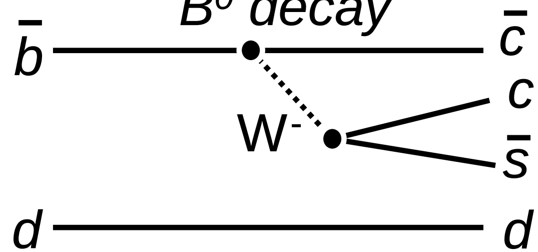
$\sin 2\beta$ from mixing & $b \to c\bar{c}s$ "tree" amplitudes

B^0 mixing



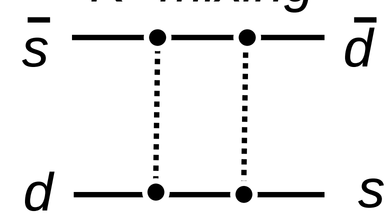
$$q/p \approx e^{-i2\beta}$$

B^0 decay



$$A \propto V_{cb}^{*} V_{cs}$$

K^0 mixing



$$q/p \propto V_{cs} V_{cd}^{*} / V_{cs}^{*} V_{cd}$$

Clean!

$$\lambda_f = \eta_f \left(\frac{q}{p}\right)_B \frac{\bar{A}_f}{A_f} \left(\frac{q}{p}\right)_K = \eta_f e^{-i2\beta}$$

THEORY:

- all decay amplitudes have the same weak phase ⇒ clean prediction

$$\mathrm{Im}(\lambda_{\psi K_S}) = -\mathrm{Im}(\lambda_{\psi K_L}) = \sin(2\beta) = S$$

$$C = 0 \qquad |\lambda_{\psi K_S}| = 1$$

EXPERIMENT:

- "Large" branching fractions, i.e.: $BF(\psi(l^+l^-)K_S(\pi^+\pi^-)) = 3.5 \times 10^{-4}$
- High purity: **up to** 97% for $J/\psi K_S$, somewhat less for other charmonium modes

Fit to tagged Δt distributions

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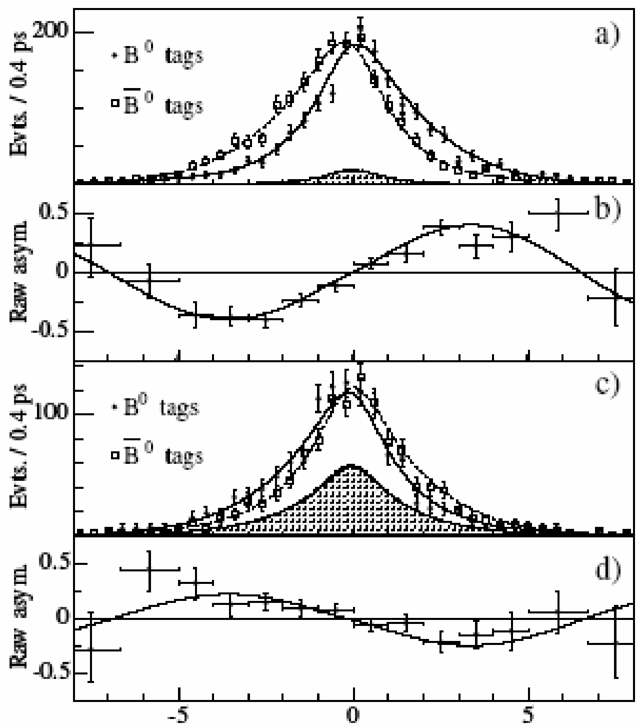
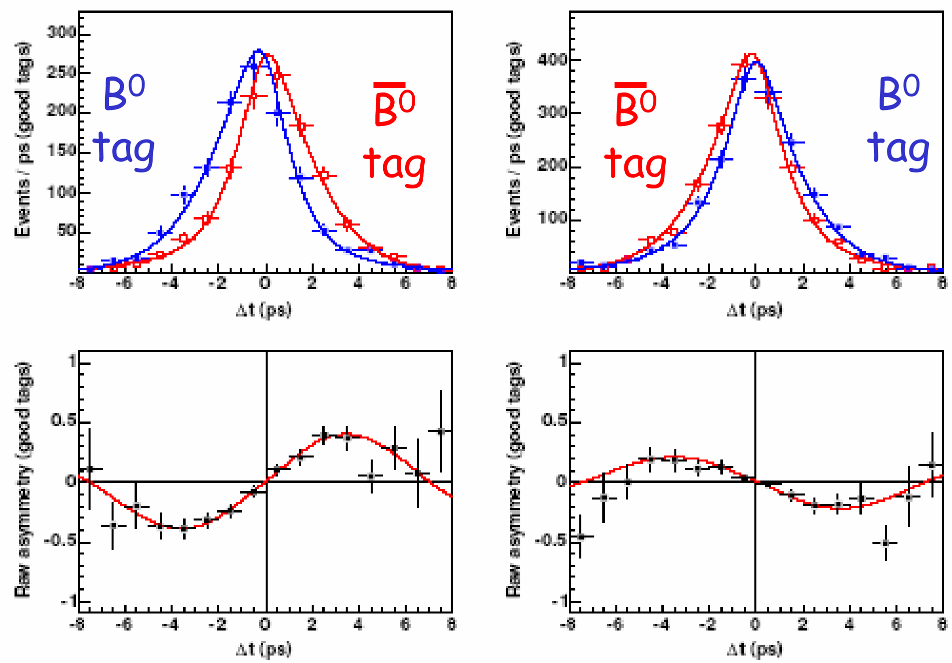
BaBar ($227 \times 10^6 B\bar{B}$)



Belle ($386 \times 10^6 B\bar{B}$)

$J/\psi K_S^0$ $J/\psi K_L^0$



$\eta_f = -1$ (above)	$\eta_f = +1$ (below)
$J/\psi K_S^0$	$J/\psi K_L^0$

etc.

$$a(\Delta t) = \underbrace{\frac{2Im\lambda}{1+|\lambda|^2}}_{S_f}\sin(\Delta m_d \Delta t) - \underbrace{\frac{1-|\lambda|^2}{1+|\lambda|^2}}_{C_f}\cos(\Delta m_d \Delta t)$$

$\sin 2\beta$ ($\sin 2\phi_1$) fit results

K.Abe
LP 2005

Winter 2005 Heavy Flavor Averaging Group (HFAG)

$$\sin 2\phi_1 = 0.725 \pm 0.037 \left\{ \begin{array}{l} 0.722 \pm 0.040 \pm 0.023 \text{ (BaBar } 227 \times 10^6 B\bar{B}) \\ 0.728 \pm 0.056 \pm 0.023 \text{ (Belle } 152 \times 10^6 B\bar{B}) \end{array} \right\}$$

$$C = 0.031 \pm 0.029 \left\{ \begin{array}{l} +0.051 \pm 0.033 \pm 0.014 \text{ (BaBar)} \\ -0.007 \pm 0.041 \pm 0.033 \text{ (Belle)} \end{array} \right\}$$

Excellent agreement between BaBar and Belle in spite of very different approaches for flavor-tagging and Δt fit. Techniques for time-dependent CPV analyses are well understood and constantly being refined.

LP05 update (Belle $386 \times 10^6 B\bar{B}$, $J/\psi K^0$ only)

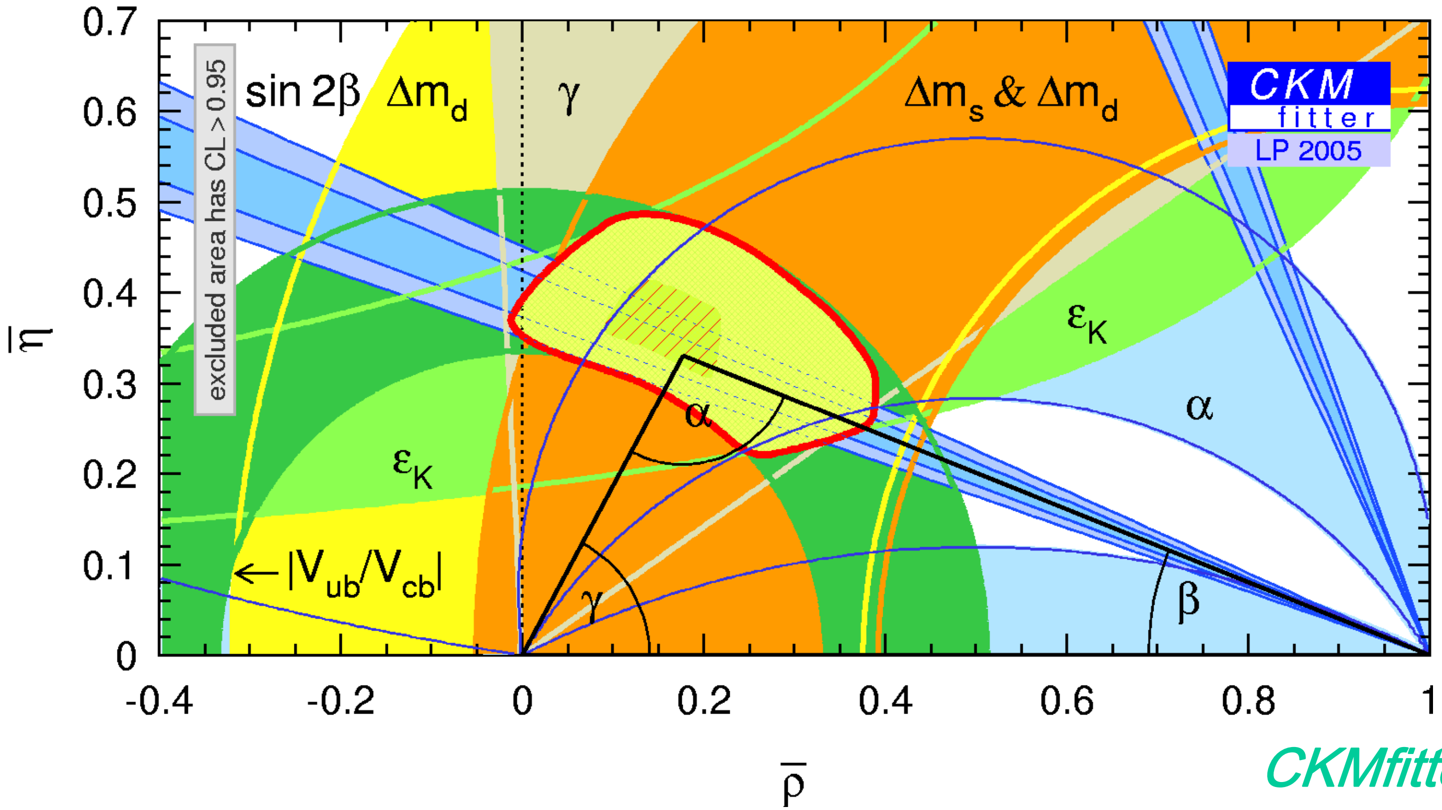
$$\sin 2\phi_1 = 0.652 \pm 0.039 \pm 0.020 \quad C = -0.010 \pm 0.026 \pm 0.036$$

New BaBar/Belle Averages

$$\sin 2\phi_1 = 0.685 \pm 0.032 \qquad C = 0.016 \pm 0.046$$

sin2β in the ($\bar{\rho}$, $\bar{\eta}$) Unitarity Plane

sin2β and the region constrained only by measurements of the sides: $|V_{ub}/V_{cb}|$, Δm_s & Δm_d, ε_K



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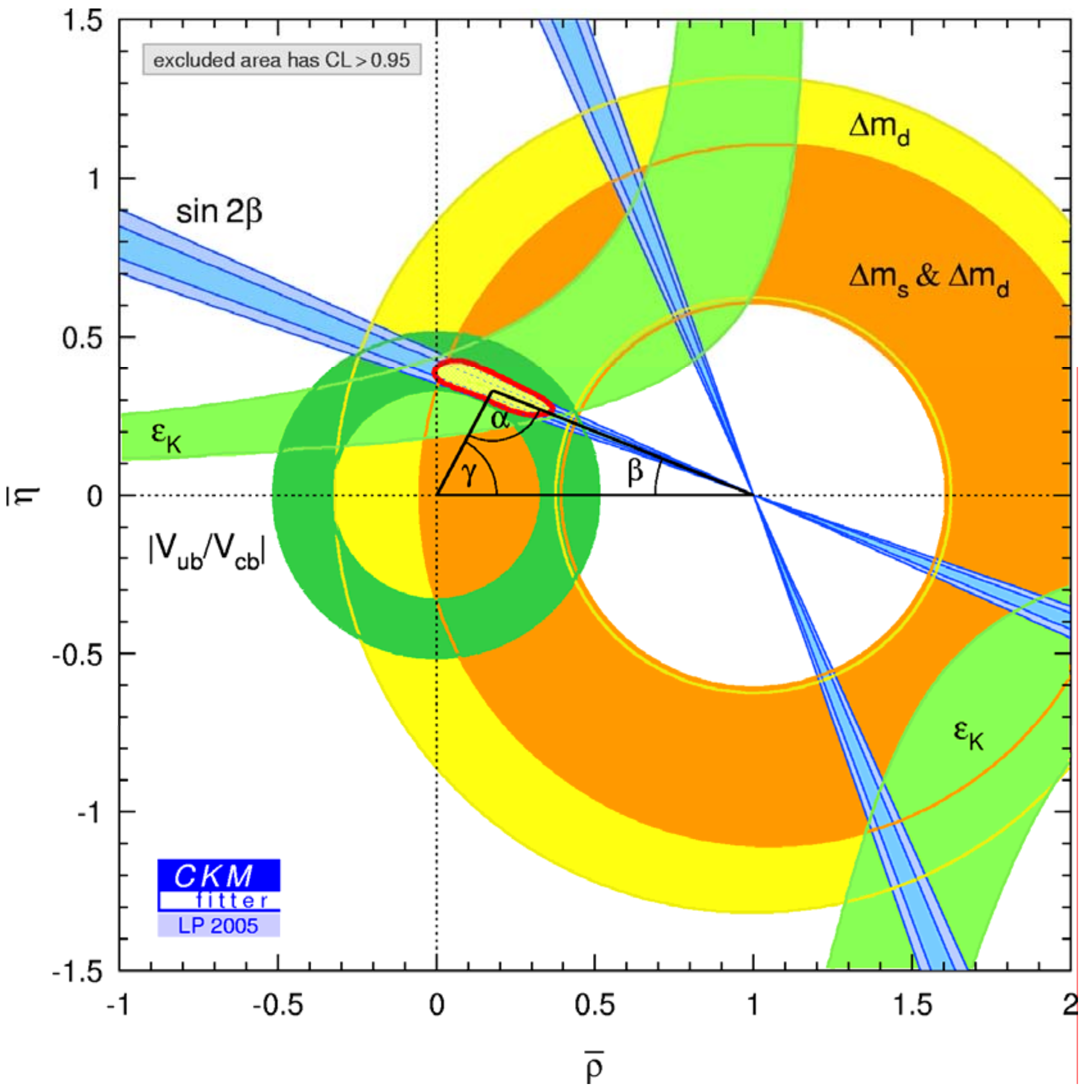
sin2β in the $(\bar{\rho}, \bar{\eta})$ Unitarity Plane

Including in the fit
sin2β
and the measurements
of the sides:
$|V_{ub}/V_{cb}|$, Δm_s & Δm_d, ε_K



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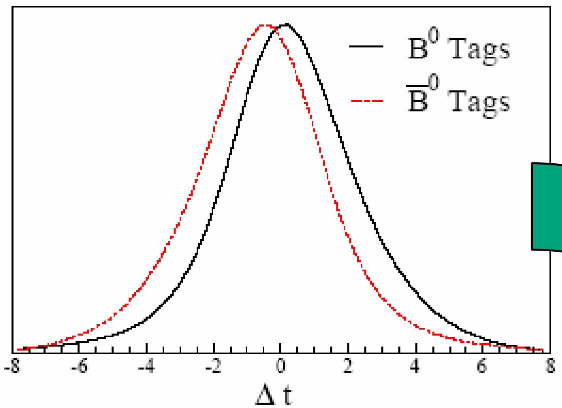
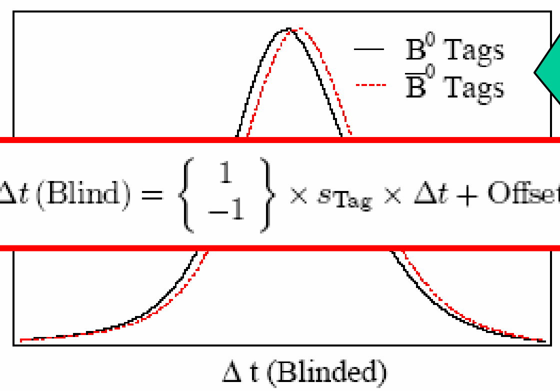
CP Analysis: a Blind Analysis

Blind Analysis in Particle Physics → Exciting "unblinding parties"…

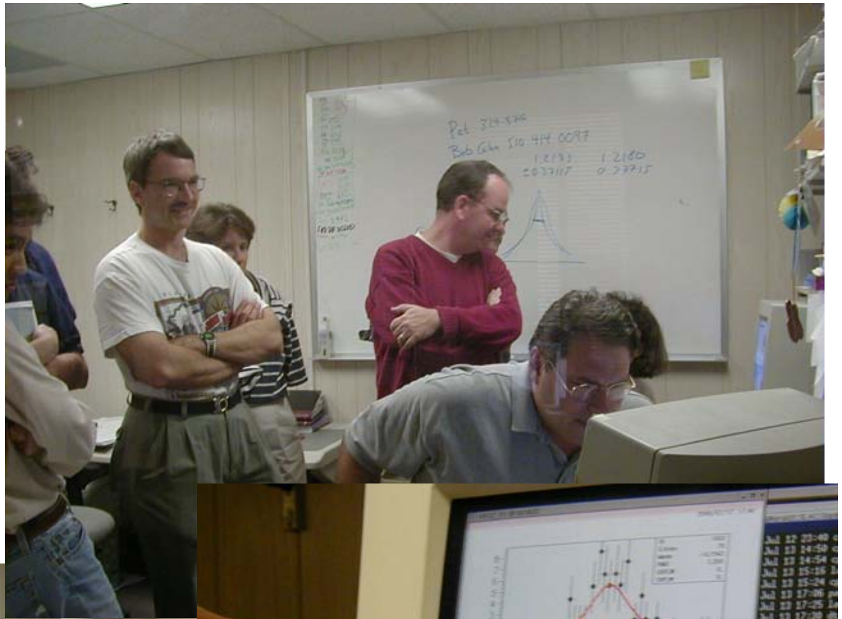
Aaron Roodman
Stanford Linear Accelerator Center, Stanford, CA 94025, USA
PHYSTAT2003, SLAC, Stanford, California, September 8-11, 2003

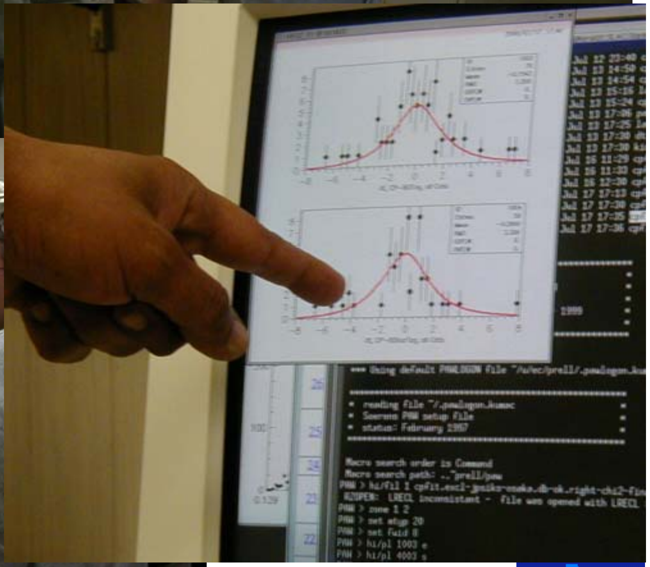


Blinded…



$$\Delta t\,(\mathrm{Blind}) = \left\{ \begin{array}{c} 1 \\ -1 \end{array} \right\} \times s_{\mathrm{Tag}} \times \Delta t + \mathrm{Offset}$$

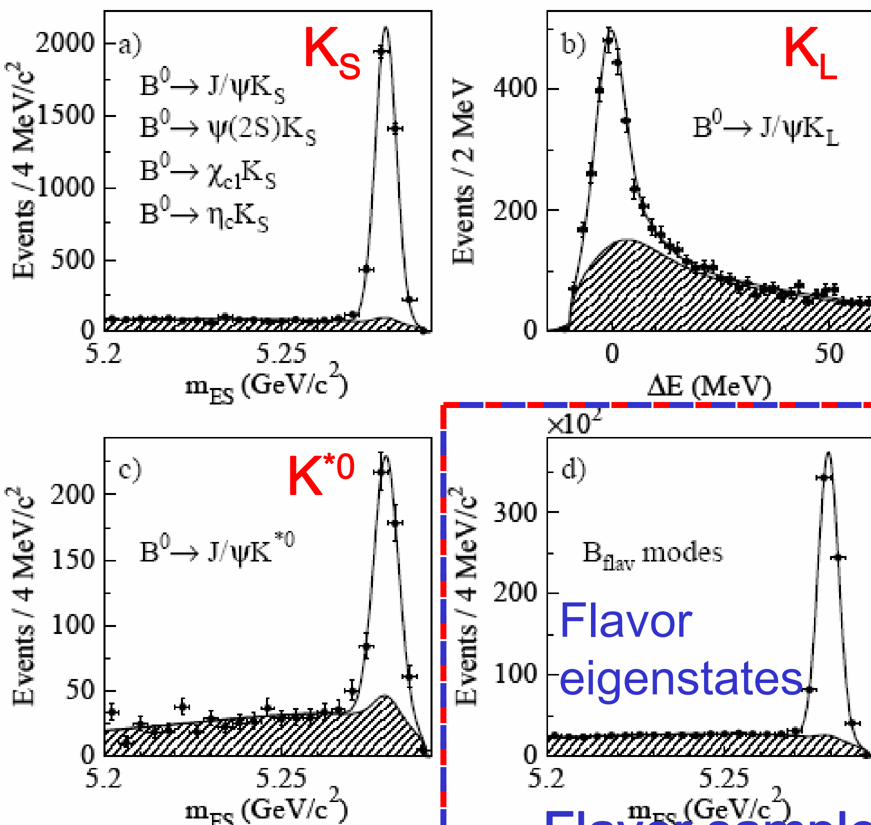




CP Analysis: event samples

CP sample: 7730 ev.

BaBar analysis, 2004



Flavor sample 72878 ev.

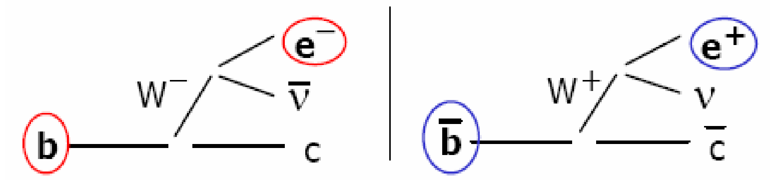
Sample	N_{tag}	$P(\%)$	$\sin 2\beta$
Full CP sample	7730	76	0.722 ± 0.040
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_c K_S^0$	4370	90	0.75 ± 0.04
$J/\psi K_L^0$	2788	56	0.57 ± 0.09
$J/\psi K^{*0}(K^{*0} \to K_S^0 \pi^0)$	572	68	0.96 ± 0.32
1999-2002 data	3032	77	0.74 ± 0.06
2003-2004 data	4698	77	0.71 ± 0.05
$J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$ only ($\eta_f = -1$)			
$J/\psi K_S^0$ ($K_S^0 \to \pi^+\pi^-$)	2751	96	0.79 ± 0.05
$J/\psi K_S^0$ ($K_S^0 \to \pi^0\pi^0$)	653	88	0.65 ± 0.12
$\psi(2S)K_S^0$ ($K_S^0 \to \pi^+\pi^-$)	485	82	0.88 ± 0.14
$\chi_{c1}K_S^0$	194	81	0.69 ± 0.23
$\eta_c K_S^0$	287	64	0.17 ± 0.25
Lepton category	490	96	0.75 ± 0.08
Kaon I category	648	93	0.75 ± 0.08
Kaon II category	1021	89	0.77 ± 0.09
Kaon-Pion category	769	90	0.77 ± 0.15
Pion category	835	87	0.96 ± 0.22
Other category	607	88	0.23 ± 0.51
B_{flav} sample	72878	85	0.021 ± 0.013
B^+ sample	18294	88	0.003 ± 0.020

Control sample 18294 ev.

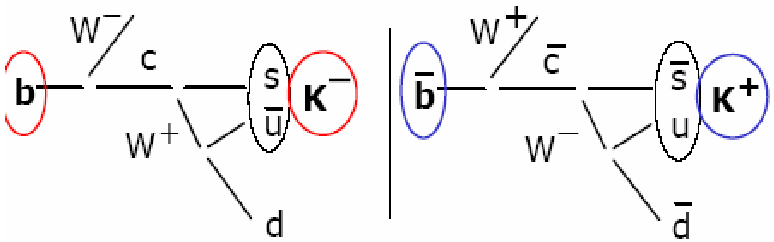
CP analysis: B Flavour Tagging

Tagging efficiency extracted from measurement of the dilution of mixing in the "flavor sample", where missing and wrong tags dilute the amplitude of the oscillation

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Soft and hard pion tagging

$$\bar{B}^0 \to D^{*+}\pi^-$$

$$\hookrightarrow D^0\pi^+$$

$\bar{B}^0$: fast π^-, soft π^+

B^0: fast π^+, soft π^-

TABLE I: Efficiencies ϵ_i, average mistag fractions w_i, mistag fraction differences $\Delta w_i \equiv w_i(B^0) - w_i(\bar{B}^0)$, and Q extracted for each tagging category i from the $B_{\rm flav}$ sample.

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.6 ± 0.1	3.2 ± 0.4	-0.2 ± 0.8	7.5 ± 0.2
Kaon I	10.9 ± 0.1	4.6 ± 0.5	-0.7 ± 0.9	9.0 ± 0.2
Kaon II	17.1 ± 0.1	15.6 ± 0.5	-0.7 ± 0.8	8.1 ± 0.2
Kaon-Pion	13.7 ± 0.1	23.7 ± 0.6	-0.4 ± 1.0	3.8 ± 0.2
Pion	14.5 ± 0.1	33.0 ± 0.6	5.1 ± 1.0	1.7 ± 0.1
Other	10.0 ± 0.1	41.1 ± 0.8	2.4 ± 1.2	0.3 ± 0.1
All	74.9 ± 0.2			30.5 ± 0.4

$$\sum_i \varepsilon_i (1-2\omega_i)^2 = 30.5 \pm 0.4\%$$

ε_i tag efficiency

ω_i wrong tag probability

BaBar

CP fit: likelihood parameters

Both Δm_d and $\sin 2\beta$: global unbinned maximum likelihood fit on data:

Δm_d — *tagged flavour sample*

$\sin 2\beta$ — *tagged flavour and CP samples*

parameters modelling mistag, Δt resolution and backgrounds: floated to obtain an empirical description of these properties from data

parameter	# params	Determining subsample
$\sin 2\beta$	1	CP
w & Δw	6 × 2 = 12	flavour
Δt resolution	7	flavour and CP
CP Bkgd τ	8	sidebands
Eff. differences	7	flavour
Flav Bkgd w, Δw	24	sidebands
Flav Bkgd Δt	3 + 3 = 6	sidebands

sin2β : systematic uncertainty

BaBar 2004:

TABLE III: Sources of systematic error on $\sin 2\beta$ and $|\lambda|$.

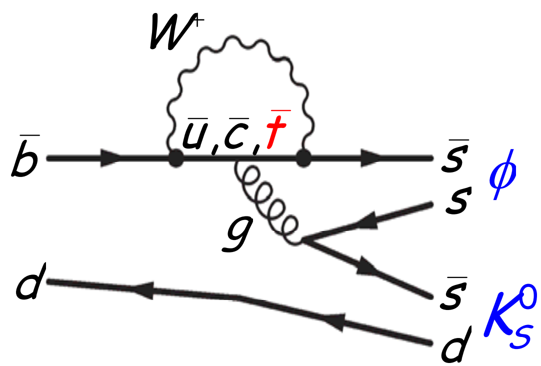
Source	$\sigma(\sin 2\beta)$	$\sigma(\|\lambda\|)$
CP backgrounds	0.012	0.002
Δt resolution function	0.011	0.003
$J/\psi K^0_L$ backgrounds	0.011	N/A
Mistag fraction differences	0.007	0.001
Beam spot	0.007	0.001
Δm_d, τ_B, $\Delta\Gamma/\Gamma$, $\|\lambda\|$	0.005	0.001
Tag-side interference	0.003	0.012
MC statistics	0.003	0.003
Total systematic error	0.023	0.013

sin2β : preliminary conclusions

- $b \rightarrow c\bar{c}s$: very good agreement with SM (CKM) expectations
- Well understood and robust analysis methods
- The same methods can be applied to more challenging channels, looking for non-SM effects: $b \rightarrow s\bar{s}s$

sin2β from mixing & *b→s* "penguin" amplitudes

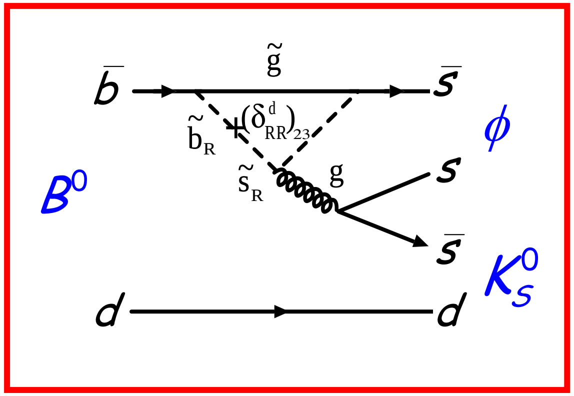
- The CKM model passed its first precision test !
  - The determination of (ρ,η) is now dominated by the measurement of sin2β: what next ?
- Start looking for non-SM effects
  - Best candidates: decays with the same (zero) weak phase, but loop ("penguin") diagrams
  - Look for effects of virtual non-SM particles in the loop
  - Experimentally, the best modes are ϕK_S, $\eta' K_S$; recently BaBar started also to study $\pi^0 K_S$, $f^0 K_S$, $K^*\gamma$
  - non-SM signature: pattern of different asymmetries for these channels



SM expectation:

$$\mathrm{Im}(\lambda_{\phi K_S}) = \sin(2\beta) = S$$

$$C = 0$$



sin2β from $b \to s$ "penguins"

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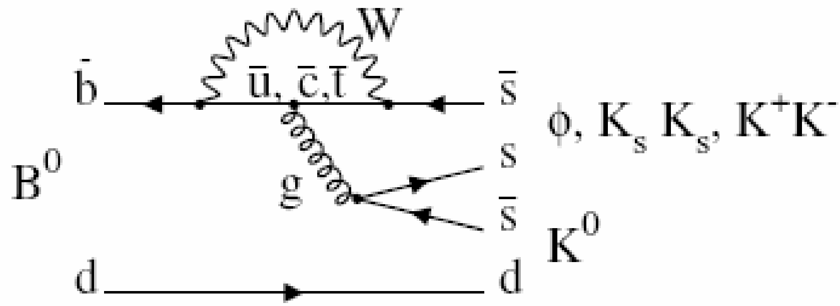
LP 2005



$$P \sim V_{ub}^* V_{us} P^u + V_{cb}^* V_{cs} P^c + V_{tb}^* V_{ts} P^t \sim \underbrace{V_{cb}^* V_{cs}}_{A\lambda^2}(P^c - P^t) + \underbrace{V_{ub}^* V_{us}}_{A\lambda^4(\rho - i\eta)}(P^u - P^t)$$

$b \to c\bar{c}s$ gives $\sin 2\phi_1$

u-quark penguin

[Unitarity relation $V_{cb}^* V_{cs} + V_{ub}^* V_{us} + V_{tb}^* V_{ts} = 0$]

- Other $b \to s$ penguins
  - $B^0 \to \eta' K^0,\ f^0 K^0$, contribution from $b \to u$ tree($\mathcal{O}(A\lambda^4(\rho - i\eta))$)
  - $B^0 \to \pi^0 K^0,\ \omega K^0$ contribution from $b \to u$ tree, $b \to s\bar{d}d$ instead of $b \to s\bar{s}s$
- SM corrections of $\mathcal{O}(\lambda^2) \sim 5\%$ possible

$sin2\beta$ from $b \to s$ "penguins"

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SM expectations

Final State	η_{cp}	S_f	C_f	Corrections
ϕK_S^0	-1	$\sin 2\phi_1$	0	u-quark penguin
ϕK_L^0	+1	$-\sin 2\phi_1$	0	
$K_S^0 K_S^0 K_S^0$	+1	$-\sin 2\phi_1$	0	
$\eta' K_S^0$	-1	$\sin 2\phi_1$	0	u-quark penguin, $b \to u$ tree
$\eta' K_L^0$	+1	$-\sin 2\phi_1$	0	
$f_0(980) K_S^0$	+1	$-\sin 2\phi_1$	0	
$K^+ K^- K_S^0$	mixture	$-(f_+ - f_-) \sin 2\phi_1$	0	
$K^+ K^- K_L^0$	mixture	$-(f'_+ - f'_-) \sin 2\phi_1$	0	
$\pi^0 K_S^0$	-1	$\sin 2\phi_1$	0	$b \to sd\bar{d}$ different from $b \to ss\bar{s}$?
ωK_S^0	-1	$\sin 2\phi_1$	0	$b \to u$ tree

$f_+ = 0.89 \pm 0.08 \pm 0.06$, $f'_- = 0.92 \pm 0.07 \pm 0.06$ (BaBar) angular moment analysis

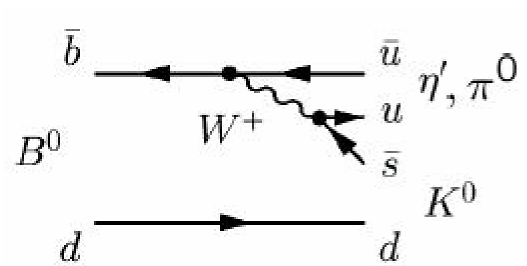
$f_+ = 0.93 \pm 0.09 \pm 0.05$ (Belle) isospin analysis

$\sin 2\beta$ from $b \to s$ "penguins": difficulties

- Experimental challenge of $b \to s$ "penguins" :
  - Smaller branching fractions
  - smaller purities

Mode	BF(B→f) $\times 10^{-6}$	$\Pi_i BF_i$ $\times 10^{-6}$	Reco. Efficiency	Purity
$J/\psi K_s$	440	36.0	44%	97%
$\eta' K_s$	33	10.6	23%	~60%
ϕK_s	4	1.4	42%	~80%
$\pi^0 K_s$	6	4.1	17%	~50%
KKK_s	25	8.6	26%	~77%

- Theoretical problems:
  - Sub-dominant SM contributions with non-zero weak phase
  - "u-quark penguin" is CKM-suppressed (~0.02), but $\eta' K_S$ and $\pi^0 K_S$ also have "$b \to u$ tree"



SM breaking of $S=\sin 2\beta$		
Mode	Reasonable expectation	Bounds* from SU(3)
ϕK_s	<0.05	<0.25
$\eta' K_s$	~0.08	<0.35
$\pi^0 K_s$	~0.08?	<0.20
KKK_s	~ 5%	< 0.25

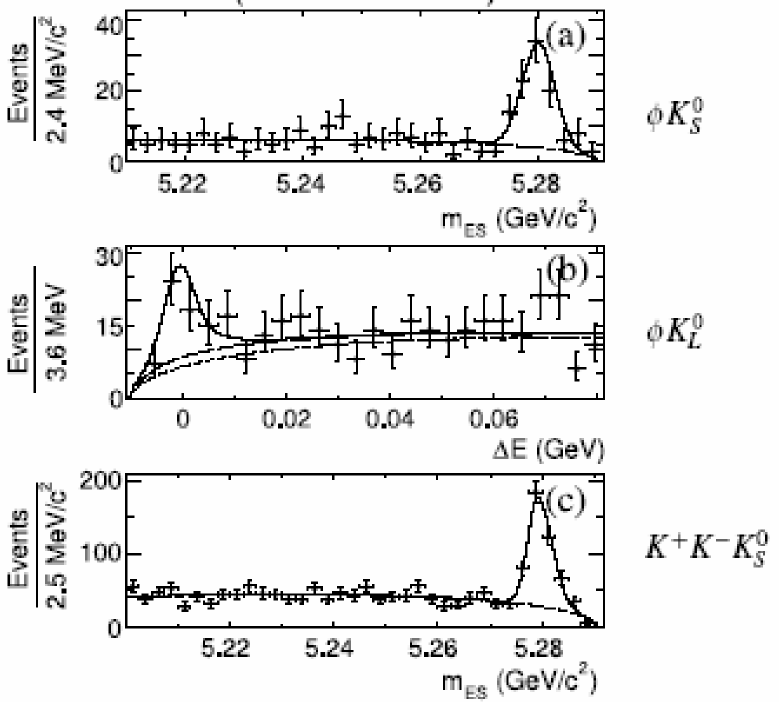
*Grossman, Ligeti, Nir, Quinn. PRD 68, 015004 (2003)
Gronau, Grossman, Rosner hep-ph/0310020

Event samples: $B^0 \to \phi K_S, \phi K_L, K^+K^-K_S$

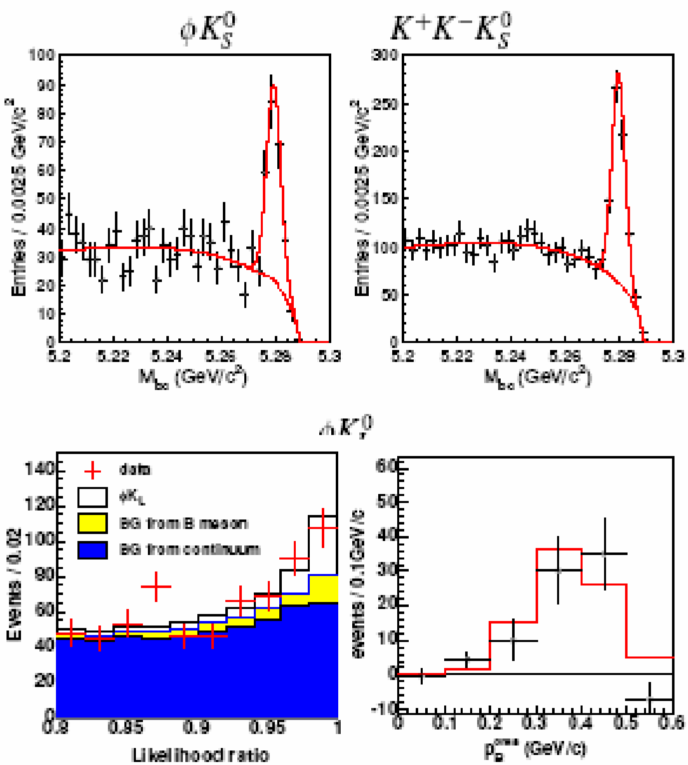
K.Abe LP 2005

- $m_B = \sqrt{E_{\rm beam}^2 - (\sum_i \vec{p}_i)^2}$ $(\sum_i E_i)^2$ is replaced by $E_{\rm beam}^2$ (signal: $m_B = 5.28$ GeV)
- $\Delta E = \sum_i E_i - E_{\rm beam}$ $E_B = E_{\rm beam}$ at B factories (i: tracks for B candidate) (signal: $\Delta E = 0$ GeV)
- For K_L^0, assume two-body decay and compute $p_{K_L^0}$

BaBar $(230 \times 10^6 B\bar{B})$



Belle $(386 \times 10^6 B\bar{B})$



Δt distributions: $B^0 \to \phi K_S, \phi K_L, K^+K^-K_S$

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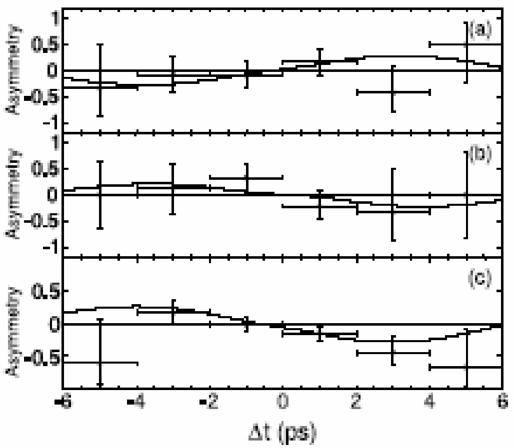
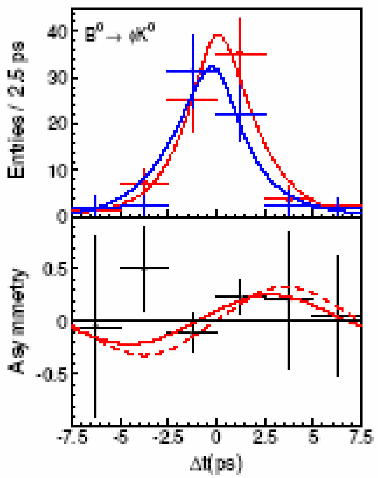
BaBar



(a) ϕK_S^0, (b) ϕK_L^0, (c) $K^+K^-K_S^0$

Belle



dotted line: Standard Model

BaBar:

$\underline{\phi K^0}$

$''\sin 2\phi_1'' = +0.50 \pm 0.25^{+0.07}_{-0.04}$

$C = 0.00 \pm 0.23 \pm 0.05$

$\underline{K^+K^-K_S^0}$

$''\sin 2\phi_1'' = +0.55 \pm 0.22 \pm 0.04 \pm 0.11\ (CP)$

$C = +0.10 \pm 0.14 \pm 0.04$

$\underline{K^+K^-K_L^0}$

$''\sin 2\phi_1'' = +0.09 \pm 0.33^{+0.13}_{-0.14} \pm 0.10\ (CP)$

Belle:

$\underline{\phi K^0}$

$''\sin 2\phi_1'' = +0.44 \pm 0.27 \pm 0.05$

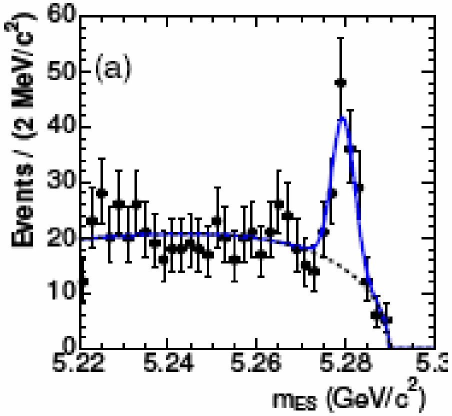
$C = -0.14 \pm 0.17 \pm 0.07$

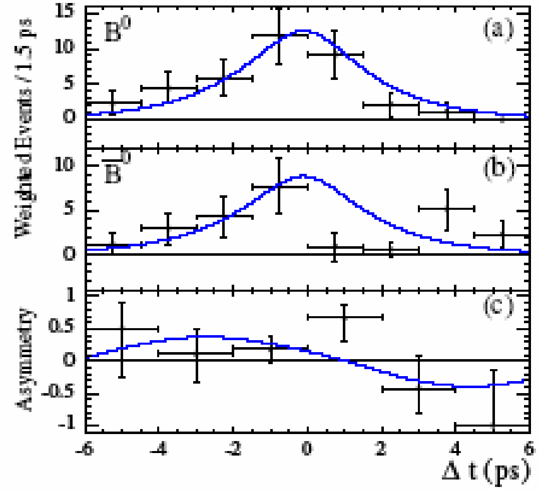
$\underline{K^+K^-K_S^0}$

$''\sin 2\phi_1 = +0.60 \pm 0.18 \pm 0.04^{+0.19}_{-0.12}(CP)$

$C = +0.06 \pm 0.11 \pm 0.07$

$B^0 \to K_S K_S K_S$ (plots from BaBar)





- At least two $K_S^0 \to \pi^+\pi^-$ "tracks" (allow one $K_S^0 \to \pi^0\pi^0$)
- Interception of three K_S^0 tracks from IP-constrained fit gives z_{CP}

$\sigma_{z_{CP}} = 75\ \mu\mathrm{m}$ (comparable to $50\ \mu\mathrm{m}$ for $J/\psi K_S^0$)

$\sigma_{\Delta z} \simeq 200\ \mu\mathrm{m}$ is still dominated by tagging-side resolution

K.Abe LP 2005

BaBar

$$"\sin 2\phi_1" = 0.63^{+0.32}_{-0.28} \pm 0.04$$
$$C = -0.10 \pm 0.25 \pm 0.05$$

Belle

$$"\sin 2\phi_1" = 0.58 \pm 0.36 \pm 0.08$$
$$C = -0.50 \pm 0.23 \pm 0.06$$

$B^0 \to \eta' K_S$, $\eta' K_L$ (plots from Belle)

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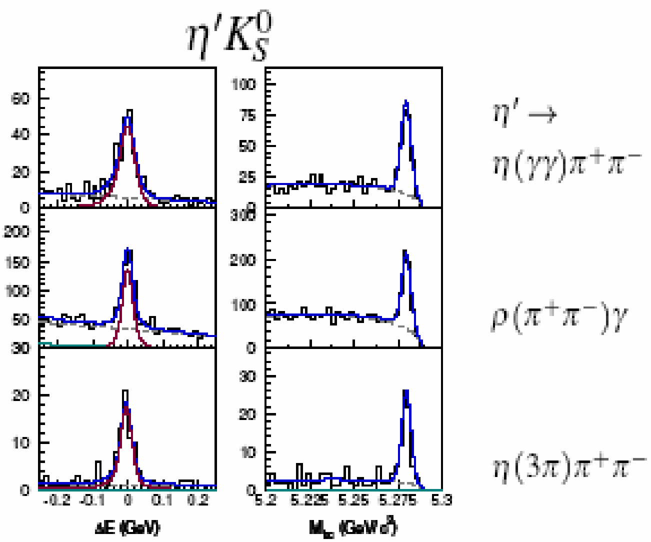
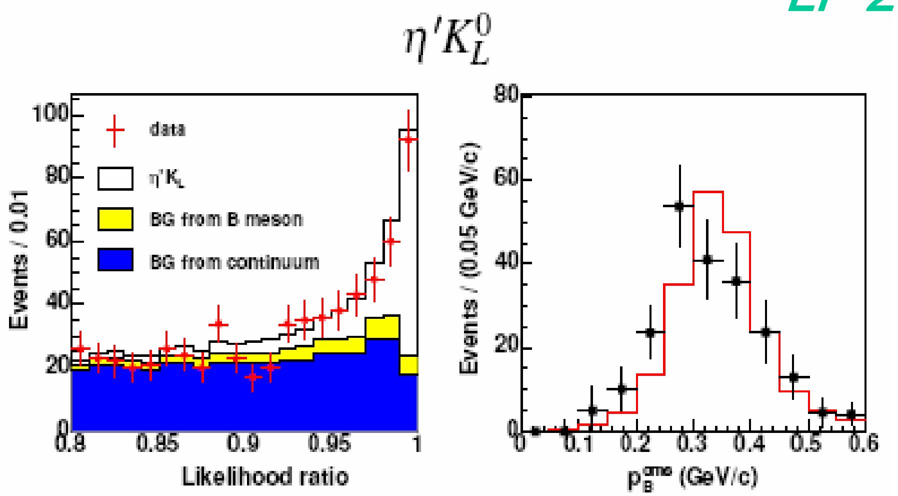


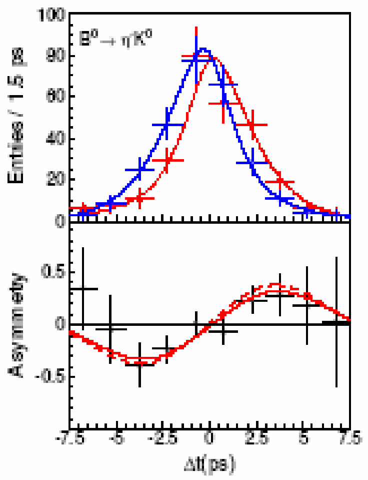


Belle $\eta' K^0$

$$"\sin 2\phi_1" = 0.62 \pm 0.12 \pm 0.04$$
$$C = 0.04 \pm 0.08 \pm 0.06$$

BaBar $\eta' K_S^0$

$$"\sin 2\phi_1" = 0.30 \pm 0.14 \pm 0.02$$
$$C = -0.21 \pm 0.10 \pm 0.02$$



$sin2\beta$ from $b \to s$ "penguins": conclusions

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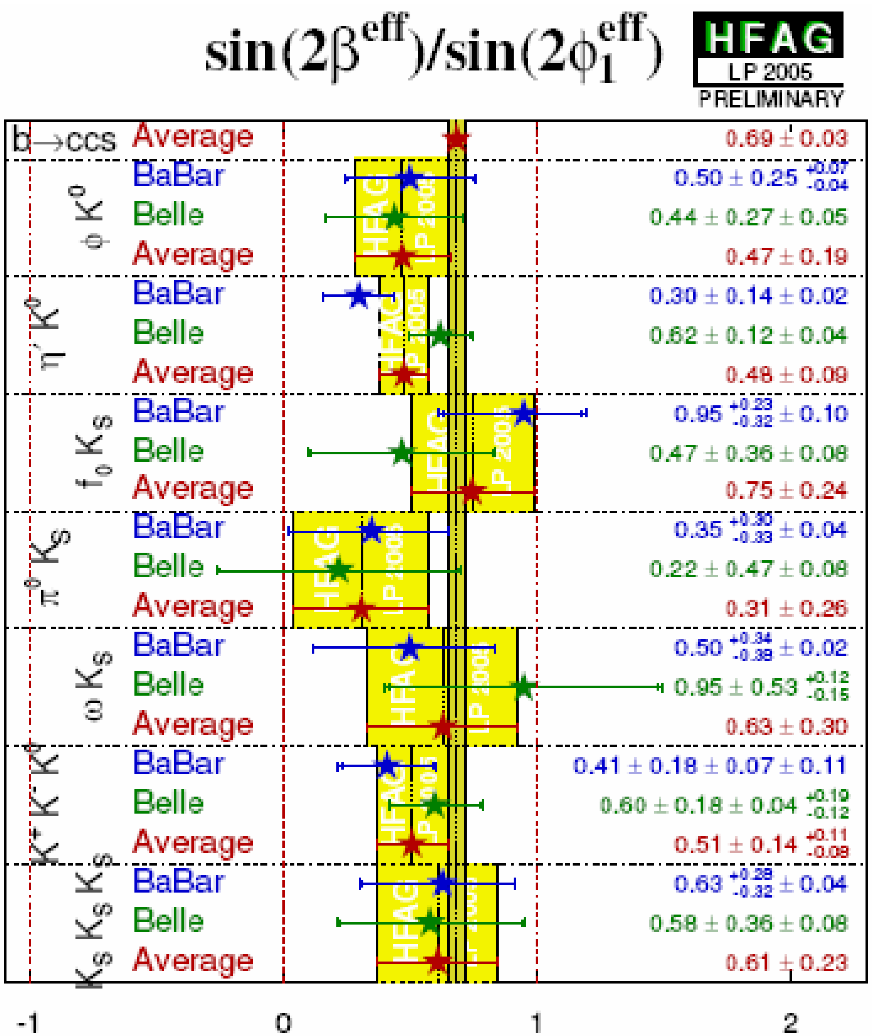

Deviation from $\sin 2\phi_1$ value

$$\Delta S \equiv \text{``}\sin 2\phi_1'' - \sin 2\phi_1$$

- All except $\eta' K^0$ are within $\sim 1\sigma$
- All except $f_0 K_S^0$ have $\Delta S < 0$
- No choice but to go for higher precision measurements

Four-Fold Ambiguity of $\phi_1 \ (\beta)$

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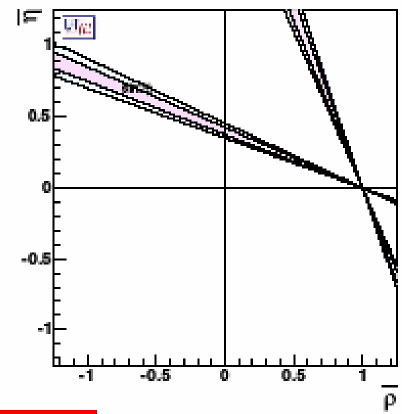
$$\sin 2\phi_1 = 0.685 \pm 0.032 \rightarrow \begin{cases} 23\ (+180)^\circ \\ 67\ (+180)^\circ \end{cases}$$



$\cos 2\phi_1$ from time-dependent angular analysis of $B^0 \rightarrow J/\psi K^{*0}(K_S^0\pi^0)$

- Sign ambiguity due to two choices of strong phases in the helicity amplitudes
- BaBar $(88 \times 10^6 B\bar{B})$: Resolve the strong phase ambiguity δ by examining S-wave and P-wave interference near $K^*(892)$

  $\cos 2\phi_1 = +2.72^{+0.50}_{-0.79} \pm 0.27$ (fix $\sin 2\phi_1 = 0.731$)

  Prefer $23^\circ\ (+180^\circ)$ solution at 86% CL
- Belle $(275 \times 10^6 B\bar{B})$: Assume s-quark helicity conservation (agrees with BaBar solution)

  $\cos 2\phi_1 = +0.87 \pm 0.74 \pm 0.12$ (fix $\sin 2\phi_1 = 0.726$)

Belle: time-dependent Dalitz analysis $B^0 \rightarrow Dh^0, \quad D \rightarrow K_S^0\pi^+\pi^-$

$\phi_1 = (16 \pm 21 \pm 12)^\circ$ (95% CL region $-30^\circ < \phi_1 < 62^\circ$)
Exclude $\phi_1 = 67^\circ$ solution at 95% CL

Summary of Lecture 4

- sin2β measurements:
  - b → ccs : very good agreement with SM (CKM) expectations
  - b → sss : ϕK_S update from Belle now consistent with BaBar and compatible with the SM
  - b → sss : all compatible with the SM within ≈ 1σ , except $\eta' K_S$; all below the SM except $f_0 K_S$; more data needed to understand if there is a non-SM effect or not

- Next, lecture 5:
  - Review of results on ππ, ρπ, ρρ and implications for sin2α
  - Measurements of γ
  - Wrap-up on the Unitarity Triangle and CKM fits