CP violation and related issues

Part 5+6: angle $\phi_1(\beta)$

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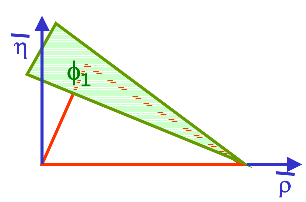


CP asymmetry

CP asymmetry:

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP},t) - P(B^0 \to f_{CP},t)}{P(\overline{B}^0 \to f_{CP},t) + P(B^0 \to f_{CP},t)} =$$

$$= \frac{-(1-|\lambda_{f_{CP}}|^2)\cos(\Delta m t) + 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1+|\lambda_{f_{CP}}|^2}$$

$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$\not{CP}$ in decay: $|\overline{A}/A| \neq 1$

$\not{CP}$ in mixing: $|q/p| \neq 1$

$\Big\}\ |\lambda| \neq 1$

$\not{CP}$ in interference between mixing and decay: $|\lambda| = 1$, $\mathrm{Im}(\lambda) \neq 1$

Decay asymmetry predictions –J/ψK$_S$

$\boxed{b \to c\bar{c}s:}$ Take into account that we measure the $\pi^+\pi^-$ component of K_S – also need the $(q/p)_K$ for the K system

Tree contribution:

$(q/p)_B$ $\quad \overline{A}/A$ $\quad (q/p)_K$

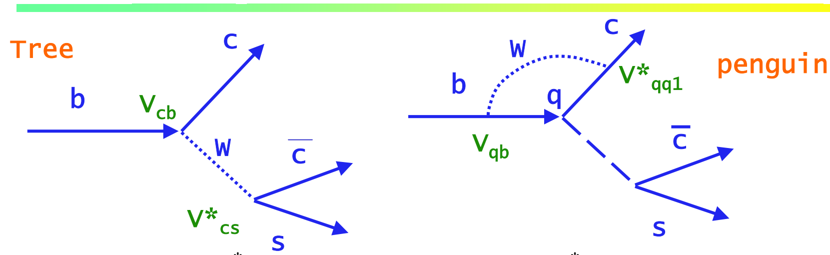
$$\lambda_{\psi K_S} = \eta_{\psi K_S} \underbrace{\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)}_{(q/p)_B} \underbrace{\left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)}_{\overline{A}/A} \underbrace{\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)}_{(q/p)_K} =$$

$$= \eta_{\psi K_S} \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb}}{V_{cb}^*}\frac{V_{cd}^*}{V_{cd}}\right)$$

$$\beta \equiv \phi_1 \equiv \arg\left(\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right)$$

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

Penguins b->ccs decays?



$$A(c\bar{c}s) = V_{cb}V_{cs}^*(T_{c\bar{c}s} + P_s^c - P_s^t) + V_{ub}V_{us}^*(P_s^u - P_s^t)$$

How much does P contribute?

- Few percent to the first term $V_{cb}V_{cs}^* = A\lambda^2$
- The second (P only) term contributes ~0.1%

$$r_{penguin} = \frac{P^t - P^u}{T} \approx \frac{\alpha_s}{12\pi}\ln\frac{m_t^2}{m_b^2} \approx O(0.03)$$

$$r_{penguin}\left(\frac{V_{us}^* V_{ub}}{V_{cb}V_{cs}^*}\right) \approx r_{penguin}\lambda^2 \approx O(10^{-3})$$

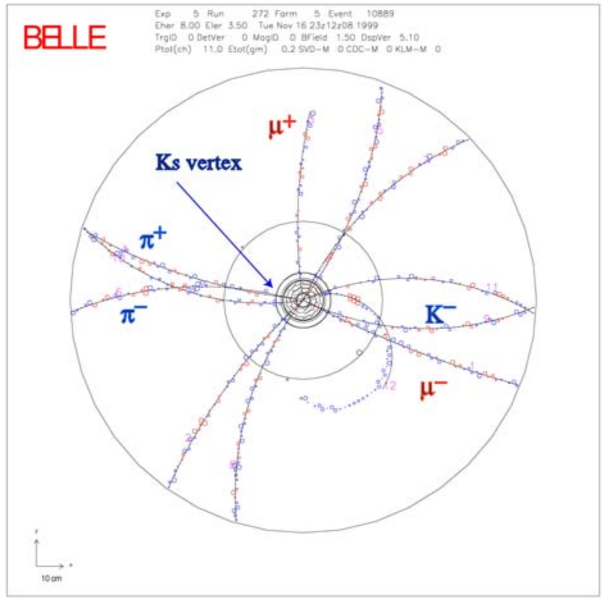
Reconstructing chamonium states

Reconstructing final states X which decayed to several particles (x,y,z):
From the measured tracks calculate the invariant mass of the system (i=x,y,z):

$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

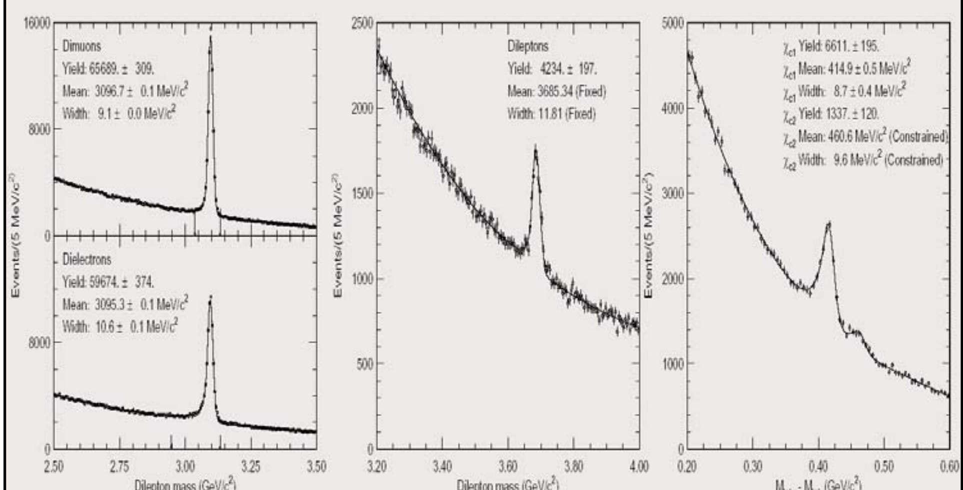
The candidates for the X->xyz decay show up as a peak in the distribution on (mostly combinatorial) background.
The name of the game: have as little background under the peak as possible without loosing the events in the peak (=reduce background and have a small peak width).

A golden channel event



May 17-25, 2005

Reconstructing chamonium states

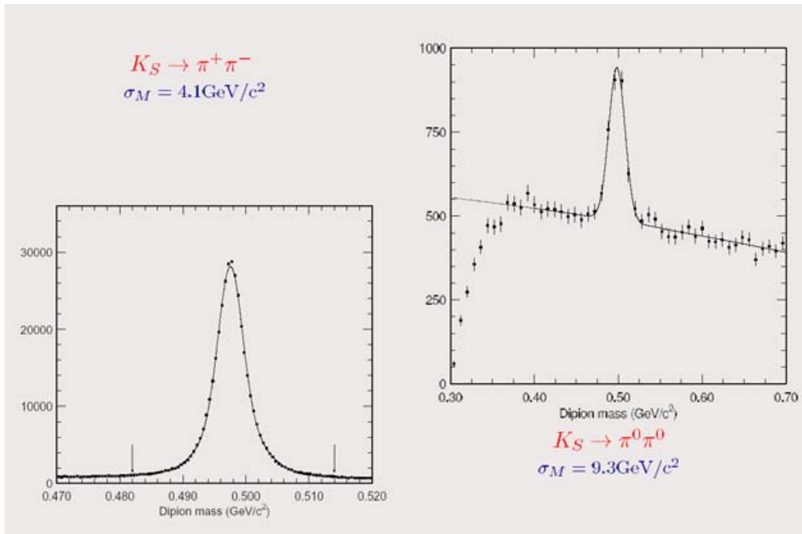


$J/\psi \to \mu^+\mu^-, e^+e^-$ $\sigma_M = 9.6(10.7)\mathrm{GeV}/c^2$

$\psi(2s) \to \mu^+\mu^-, e^+e^-$ $\sigma_M = 12.1\mathrm{GeV}/c^2$

$\chi_{c1}, \chi_{c2} \to J/\psi\gamma$ $\sigma_{\Delta M} = 7.0\mathrm{GeV}/c^2$

Reconstructing K^0_S



Reconstruction B meson decays

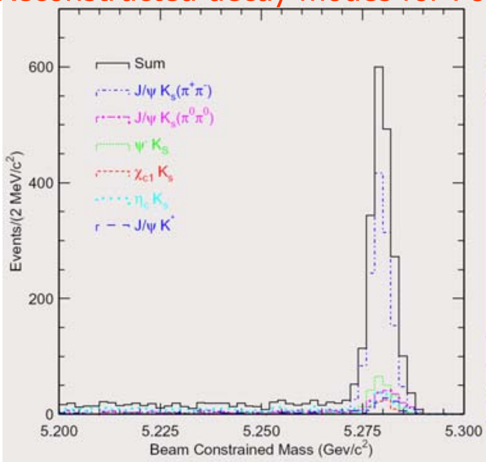
Reconstructing B meson decay at Y(4s):
Improve the resolution by taking into account that only two B mesons are produced in an Y(4s) decay.
In the expression for the invariant mass use the energy of the beam in cms (1/2 total energy in cms) instead of the reconstructed energy (which involves information on particle identification)

-> **beam constrained mass M_{bc}**

$$\boxed{M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}}$$

Reconstruction of b-> c anti-c s
CP=-1 eigenstates

Reconstructed decay modes for 78/fb, 85M B B pairs, Belle 2002 result



$$M_{bc} = \sqrt{E^2_{\text{beam}} - \vec{p}^{\,2}_{\text{Bcandidate}}}$$

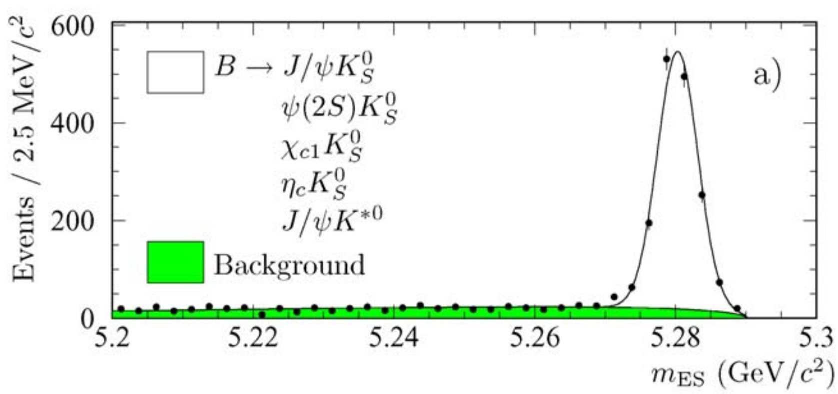
$B^0 \to$	events	$\frac{S}{S+N}$
$J/\psi K_S (K_S \to \pi^+\pi^-)$	1285	.976
$J/\psi K_S (K_S \to \pi^0\pi^0)$	188	.824
$\psi(2S) K_S$		
$(\psi(2S) \to \ell^+\ell^-) K_S$	91	.957
$(\psi(2S) \to J/\psi \pi^+\pi^-)$	112	.911
$\chi_{c1} K_S$	77	.958
$\eta_c(\eta_c \to K_S K \pi) K_S$	72	.646
$\eta_c(\eta_c \to K K \pi^0) K_S$	49	.725
$\eta_c(\eta_c \to p\bar{p}) K_S$	21	.936
$J/\psi K^*(K^* \to K_S \pi^0)$	101	.917
total $CP = -1$	1996	.935
$J/\psi K_L$, $CP = +1$	1330	.627
Total	3326	.807

2958 events are used in the fit

Reconstruction of b-> c anti-c s
CP=-1 eigenstates

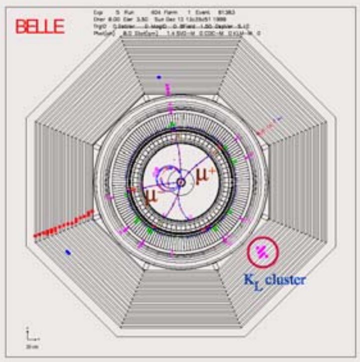
$J/\Psi(\Psi,\chi_{c1},\eta_c)$ $K_s(K^{*0})$ sample $(\eta_f=-1)$
from $88(85)\times10^6$ $B\bar{B}$

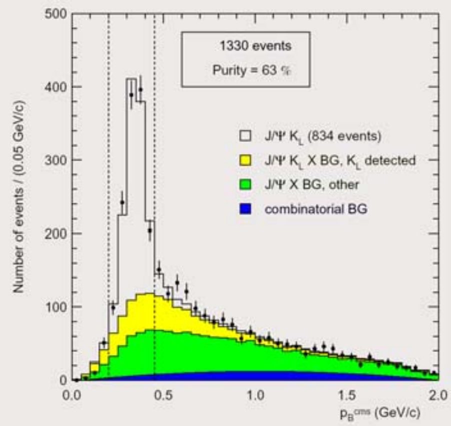
BaBar 2002 result



Reconstruction of b-> c anti-c s CP=+1 eigenstates

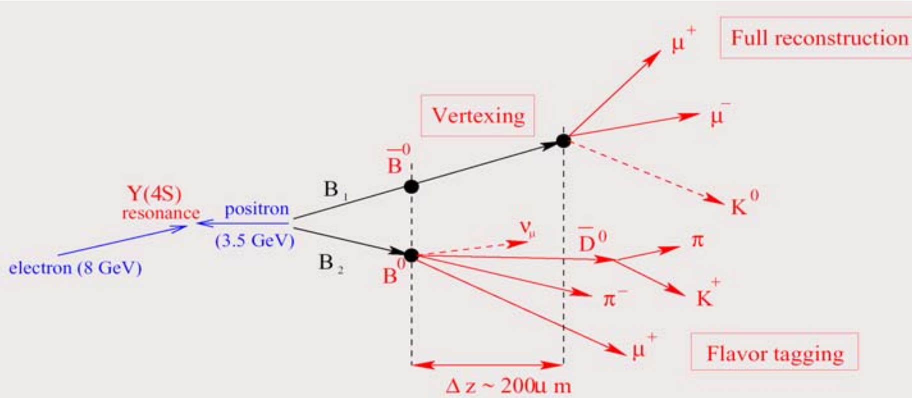
- detection of K_L in KLM and ECL
- K_L direction, no energy





- $p^* \approx 0.35$ GeV/c for signal events
- background shape is determined from MC, and its size from the fit to the data

Measurement of CP violation - continued

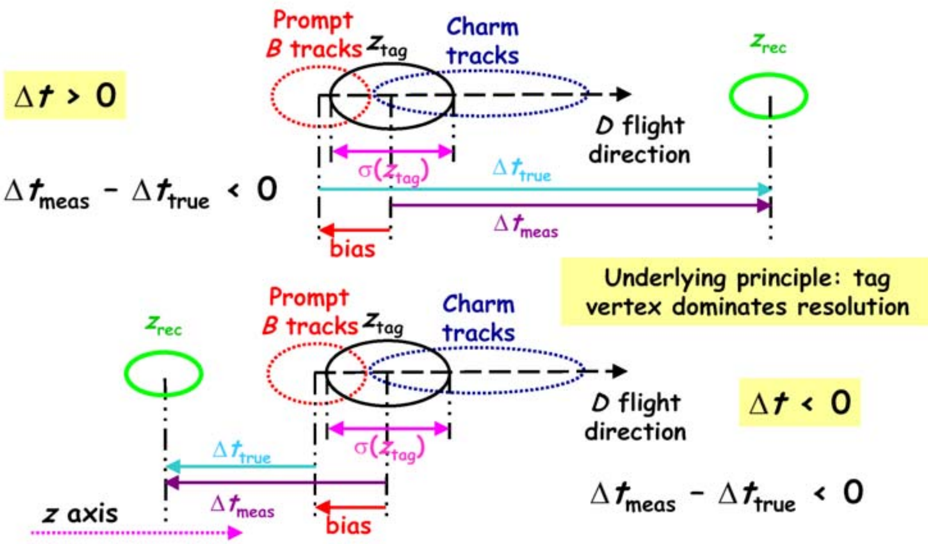


Determine Δt from $\Delta z = \beta\gamma c\Delta t$:

- clock start: resolution on tag side 140 μm ($\epsilon = 91\%$) - charm decays
- clock stop: resolution on CP side 75 μm ($\epsilon = 92\%$)

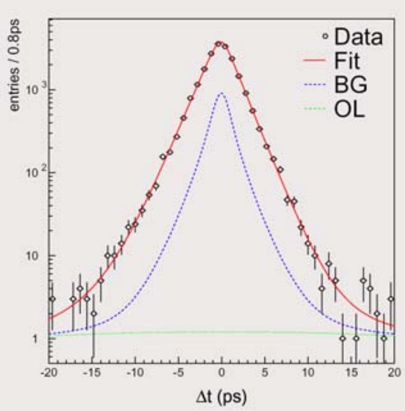
N.B. typically $\Delta z = \beta\gamma c\tau_B = 200$ μm

Effect of charm decays on time resolution



Vertexing - check with lifetime measurement

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



- time resolution: 1.43 ps
- B^0 lifetime 1.551 ± 0.018 (stat) ps (preliminary)
- PDG: 1.542 ± 0.016 ps

Flavour tagging 1

Identify $B^0/\bar{B}^0$ by the charges of the decay products of the associated B

Inclusive leptons

- high momentum ℓ^- $\quad b \to c\ell^-\nu$
- intermediate momentum ℓ^+ $\quad c \to s\ell^+\nu$

Inclusive hadrons

- high momentum π^+ $\quad B^0 \to D^{(*)-}\pi^+,\ D^{(*)-}\rho^+(\rho^+ \to \pi^+\pi^0),\ ..$
- intermediate momentum K^+ $\quad \to K^+X$
- low momentum π^- $\quad D^{(*)-} \to \bar{D}^0\pi^-$

Efficiency $> 99.5\%$, $\epsilon_{\text{effective}} = 28.8 \pm 0.5\%$

Flavour tagging 2

Tagging is not perfect: there is always a chance w that the tag is fake (less for leptons more for kaons).

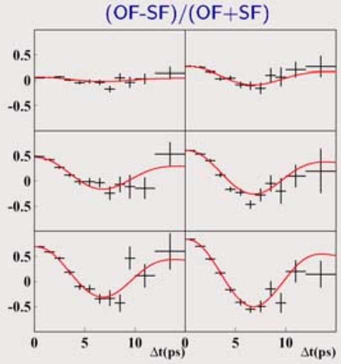
$\to$ The asymmetry oscillation is reduced, $\sin\Delta m_d t \to (1-2w)\sin\Delta m_d t$.

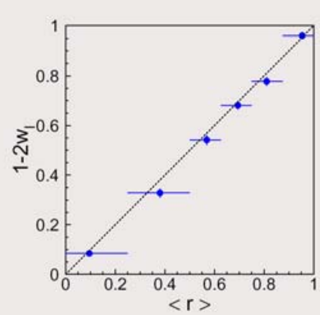
$\to$ Needed: w for each event.

Classify events into six cathegories in a tag quality variable r.

Calibrate the relation $(1-2w)$ vs. r with data: measure the $B^0\bar{B}^0$ mixing amplitude (using $\bar{B}^0 \to D^{*+}\ell^-\nu$, $D^{(*)+}\pi^-$ and $D^{(*)+}\rho^-$ decays) in 6 intervals in r

(OF-SF)/(OF+SF)



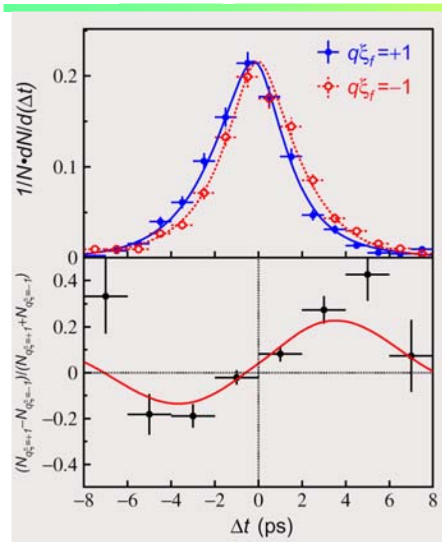


Flavour tagging 3

l	r interval	ϵ_l	w_l	$\epsilon_{\rm eff}^l$
1	0.000 – 0.250	0.398	0.458 ± 0.006	0.003 ± 0.001
2	0.250 – 0.500	0.146	0.336 ± 0.009	0.016 ± 0.002
3	0.500 – 0.625	0.104	0.228 ± 0.010	0.031 ± 0.002
4	0.625 – 0.750	0.122	$0.160\ ^{+0.009}_{-0.008}$	0.056 ± 0.003
5	0.750 – 0.875	0.094	0.112 ± 0.009	0.056 ± 0.003
6	0.875 – 1.000	0.136	0.020 ± 0.006	$0.126\ ^{+0.003}_{-0.004}$

Table: tagging efficiency, wrong tag probability and effective tagging efficiency $\varepsilon(1-2w)^2$ for six intervals in the tagging variable r.

Final result



CP is violated! Red points differ from blue.

Red points: anti-B^0 -> f_{CP} with CP=-1 (or B^0 -> f_{CP} with CP=+1)

Blue points: B^0 -> f_{CP} with CP=-1 (or anti-B^0 -> f_{CP} with CP=+1)

Belle, 2002 statistics (78/fb, 85M B B pairs)

Fitting the asymmetry

Fitting function:

$$P_{sig}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 + q(1-2w_l)\,\mathrm{Im}\,\lambda \sin \Delta m t\right\} \otimes R(t)$$

Miss-tagging probability

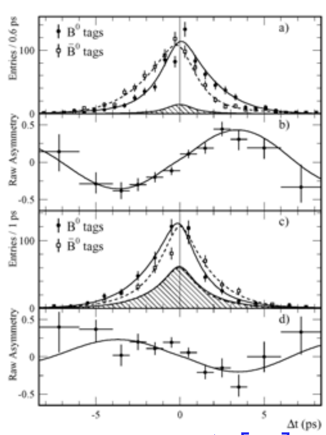
Resolution function: from self-tagged events $B \rightarrow D^* l\nu$, $D\pi$, …

q=+1 or =-1 (B or anti-B)

Fitting: unbinned maximum likelihood fit event-by-event

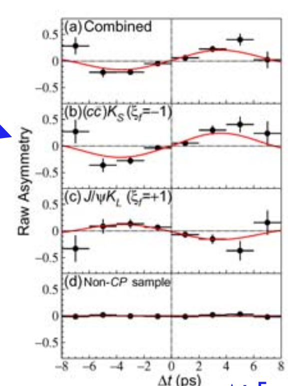
Fitted parameter: Im(λ)

BaBar vs Belle sin2ϕ_1



Δt[ps]

asymmetry



Δt[ps]

sin2ϕ_1=0.741±0.067±0.034 (BaBar)
sin2ϕ_1=0.719±0.074±0.035 (Belle)

2002 statistics

b-> c anti-c s
CP=+1 and CP=-1 eigenstates

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)$$

Asymmetry sign depends on the CP parity of the final state f_{CP}, η_{fcp}=+-1

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

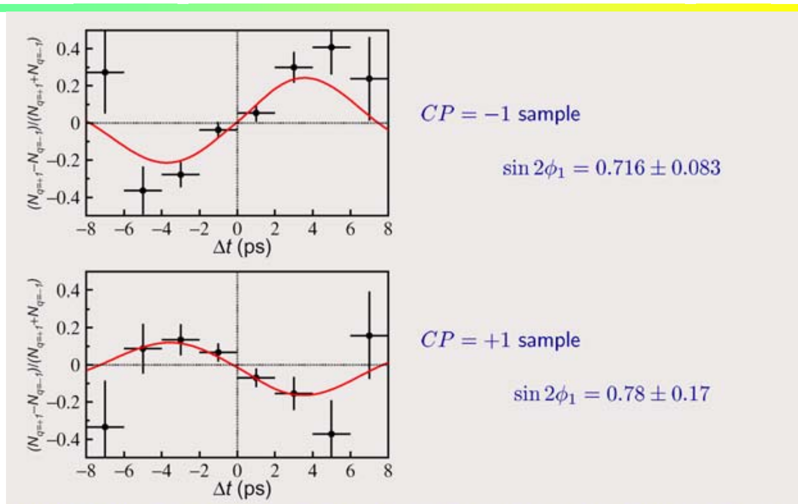
$J/\psi\ K_S\ (\pi^+ \pi^-)$: CP=-1

- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- K_S (->$\pi^+ \pi^-$): CP=+1, orbital ang. momentum of pions=0 -> P $(\pi^+ \pi^-)=(\pi^- \pi^+)$, C$(\pi^- \pi^+)$ =$(\pi^+ \pi^-)$
- orbital ang. momentum between J/ψ and K_S l=1, P=$(-1)^1$=-1

$J/\psi\ K_L(3\pi)$: CP=+1

Opposite parity to $J/\psi\ K_S\ (\pi^+ \pi^-)$, because $K_L(3\pi)$ has CP=-1

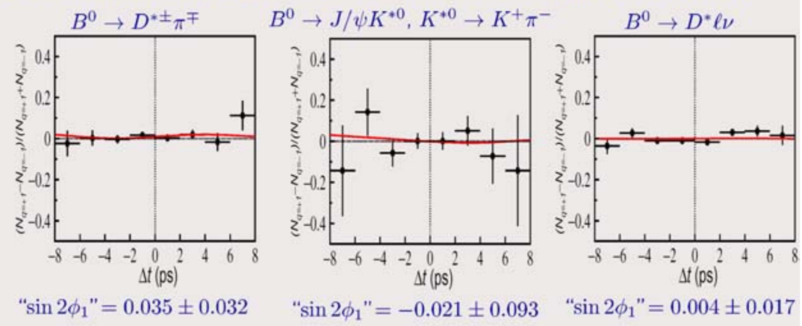
Comparison between CP=+1 and CP=-1



N.B. Plotted: raw asymmetry. The amplitude of $\pm\sin 2\phi_1 \sin\Delta m_d \Delta t$ is reduced due to wrong tagging by a factor $(1-2w)$.

Checks, systematic errors

Same analysis for flavour specific final states, where there should be no asymmetry



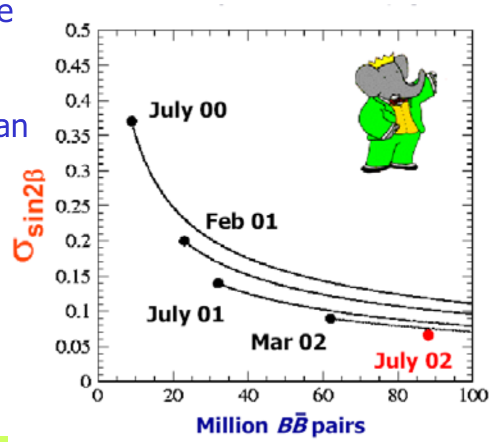
Systematic errors:

vertexing	0.022	resolution function	0.014
possible bias in $\sin 2\phi_1$ fit	0.011	$J/\psi K_L$ background fraction	0.010
Δm_d	< 0.010	τ_B	< 0.010

More data....

Larger sample ->
•smaller statistical error ($1/\sqrt{N}$)
•better understanding of the detector, calibration etc

-> error improves better than with $1/\sqrt{N}$



Fit with free |λ|

time distribution:

$$P_{sig}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 + q(1-2w_l)\left[\frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1}\sin\Delta m\Delta t + \underbrace{\frac{|\lambda|^2-1}{|\lambda|^2+1}\cos\Delta m\Delta t}_{\text{direct } \cancel{CP}}\right]\right\}$$

fit with
Imλ/|λ| and |λ| as free parameters

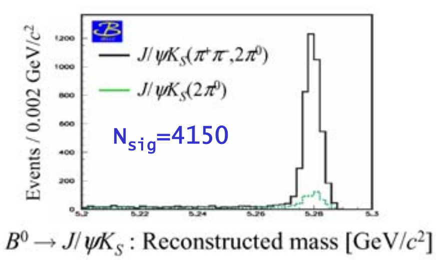
direct $\cancel{CP}$
|λ| ≠ 1

|λ|=0.950±0.049±0.025 (Belle,PRD66,071102(02))

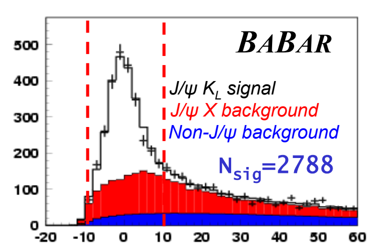
sin2ϕ_1=0.719±0.074±0.035

sin2ϕ_1 – status 2004

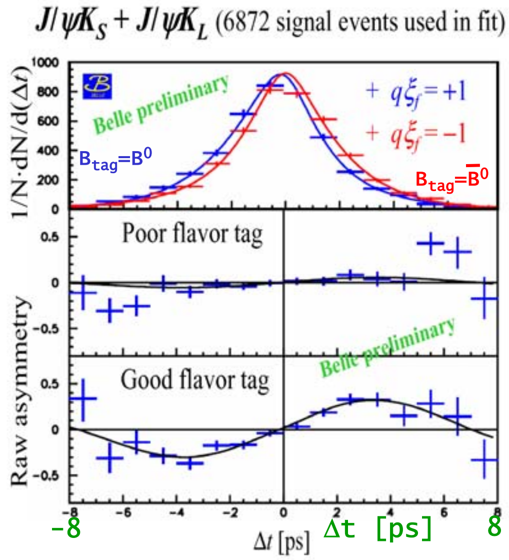
B→J/ψ K_s



B→J/ψ K_L



Considerable increase in statistics.



$\sin 2\phi_1$ – status 2004

a_{CP}

$\sin 2\phi_1 = 0.666 \pm 0.046$

Belle

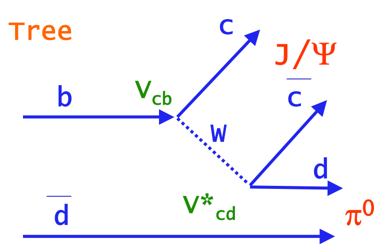
$\sin 2\phi_1 = 0.722 \pm 0.040 \pm 0.023$

BaBar

$\sin 2\phi_1(\beta)$ from other processes

$\sin 2\phi_1$ is the CP asymmetry parameter in

- $b \to ccd$ (tree+penguin)
- $b \to sss$ (penguin only)

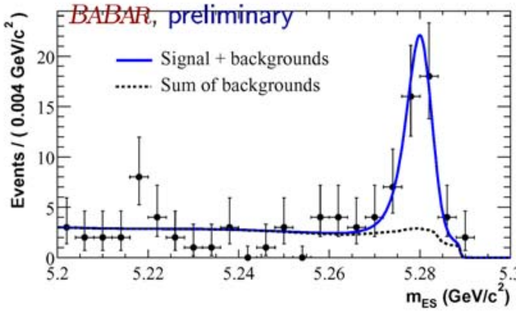


$$\lambda_{\psi Ks} = \eta_{\psi Ks}\left(\frac{V_{tb}^{\ *}V_{td}}{V_{tb}V_{td}^{\ *}}\right)\left(\frac{V_{cd}^{\ *}V_{cb}}{V_{cd}V_{cb}^{\ *}}\right)$$

$$\mathrm{Im}(\lambda_{\psi Ks}) = \sin 2\phi_1 = \sin 2\beta$$

$$A(c\bar{c}d) = V_{tb}V_{td}^{\ *}(P_d^t - P_d^u) + V_{cb}V_{cd}^{\ *}(T_{c\bar{c}d} + P_d^c - P_d^u)$$

$\sin 2\phi_1(\beta)$ from $b \to c\bar{c}d$



$B \to J/\Psi\, \pi^0$

(BaBar, hep-ex/0207058(02); Belle, hep-ex/0207058(02))

Tree and penguin contrib. $O(\lambda^3)$; remove $|\lambda_{fCP}|=1$ assumption in fit:

$$a_{f_{CP}} = \underbrace{\frac{2\,\mathrm{Im}(\lambda_{f_{CP}})}{1+|\lambda_{f_{CP}}|^2}}_{\mathcal{S}_f}\sin(\Delta m t) + \underbrace{\frac{|\lambda_{f_{CP}}|^2-1}{|\lambda_{f_{CP}}|^2+1}}_{\mathcal{A}_f}\cos(\Delta m t)$$

in leading order

$\mathcal{S}_f=-\eta_f \sin 2\phi_1$ $\mathcal{A}_f=0$

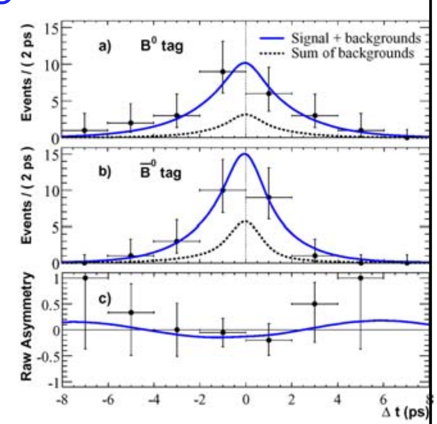
$\sin 2\phi_1(\beta)$ from $b \to c\bar{c}d$

$$a_{f_{CP}} = \underbrace{\frac{2\,\mathrm{Im}(\lambda_{f_{CP}})}{1+|\lambda_{f_{CP}}|^2}}_{\mathcal{S}_f}\sin(\Delta m t) + \underbrace{\frac{|\lambda_{f_{CP}}|^2-1}{|\lambda_{f_{CP}}|^2+1}}_{\mathcal{A}_f}\cos(\Delta m t)$$

Prediction: in leading order

$\mathcal{S}_f=-\eta_f \sin 2\phi_1$ $\mathcal{A}_f=0$

$\mathcal{S}_f=0.05\pm0.49\pm0.16$ (BaBar)
$\mathcal{A}_f=-0.38\pm0.41\pm0.09$
$\mathcal{S}_f=-0.93\pm0.49\pm0.11$ (Belle)
$\mathcal{A}_f=-0.25\pm0.39\pm0.06$



consistent with $\sin 2\phi_1$ and 0!