Measurements of time dependent CP asymmetry in $B \to VV$ decays with BELLE

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Outline

1. Introduction

2. Full time−dependent angular analysis for $B^0 \to J/\psi\ K^{*0}$

3. Time−integrated angular analysis for
   a) $B^0 \to D^{*+}D^{*-}$
   b) $B^0 \to D^{*-}\rho^+$
   c) $B^+ \to \rho^+\ \rho^0$

4. Summary

1. Introduction

- There are 3 helicity states in the final state of $B \to VV$ decay
- CP even and odd states are mixed in the final states
  $\to$ causes the dilution in the CP asymmetry
- Using angular analysis, it is possible to project out each CP state in a statistcal way.
  $\to$ useful to minimize the dilution

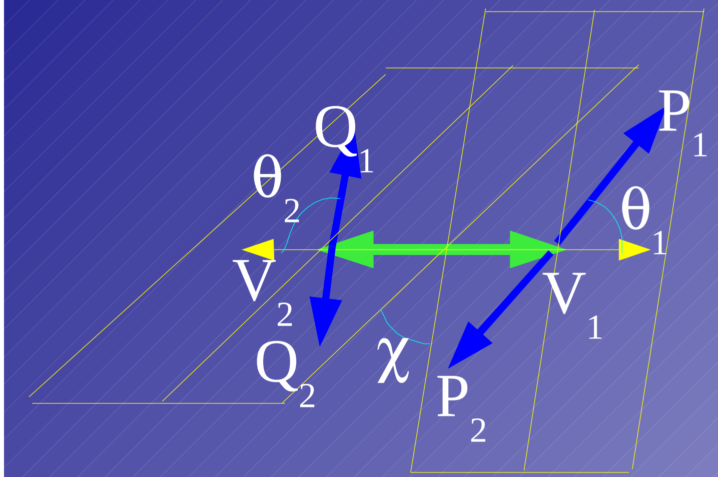
Definition of angles

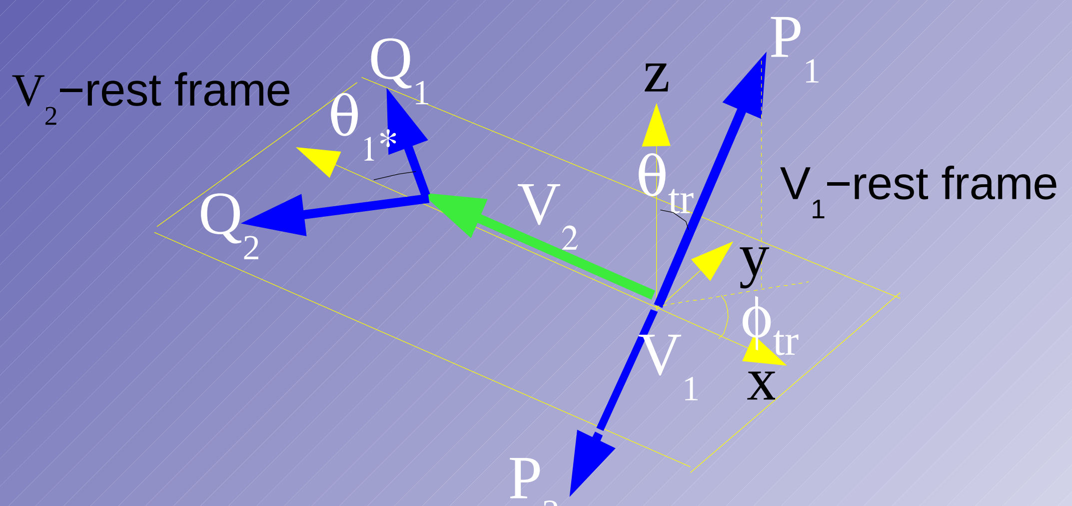
$B \rightarrow V_1 V_2$

$V_1 \rightarrow P_1 P_2$

$V_2 \rightarrow Q_1 Q_2$

Two definitions of angles





Helicity Basis

− Conventional definition

Transversity Basis

− θ_{tr} can directly be related to CP state of the system

CP violation in angular distribution

- There are 6 components in the differential angular cross section for $B \to VV$ decay.
  - components for three helicity states (3)
  - components for interferences between helicity states (3)

- Each term is a product of angular term and amplitude term.

- Amplitude terms contain CP violating phase(s) as a function of Δt (decay time difference between two B mesons from Υ(4S) decay)

  i.e. $\sin 2\phi_w \sin\Delta m \Delta t$, etc.

  ↓

  Fitting measured angles and Δt to the cross section formula

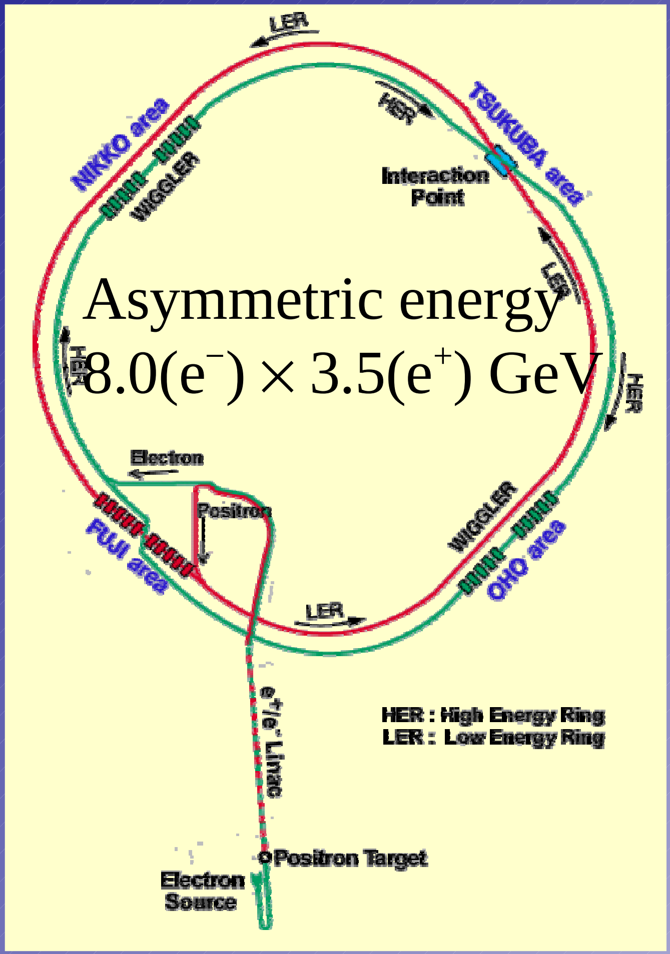
  $\to$ determination of ϕ_w

- Interference term is a rich source of interesting physics
  - $\cos 2\phi_1$ measurement ($J/\psi K^*$)
  - simultaneous determination of r and $\sin(2\phi_1+\phi_3)$ ($D^*\rho$)

Belle

B factory experiment at KEK in Japan

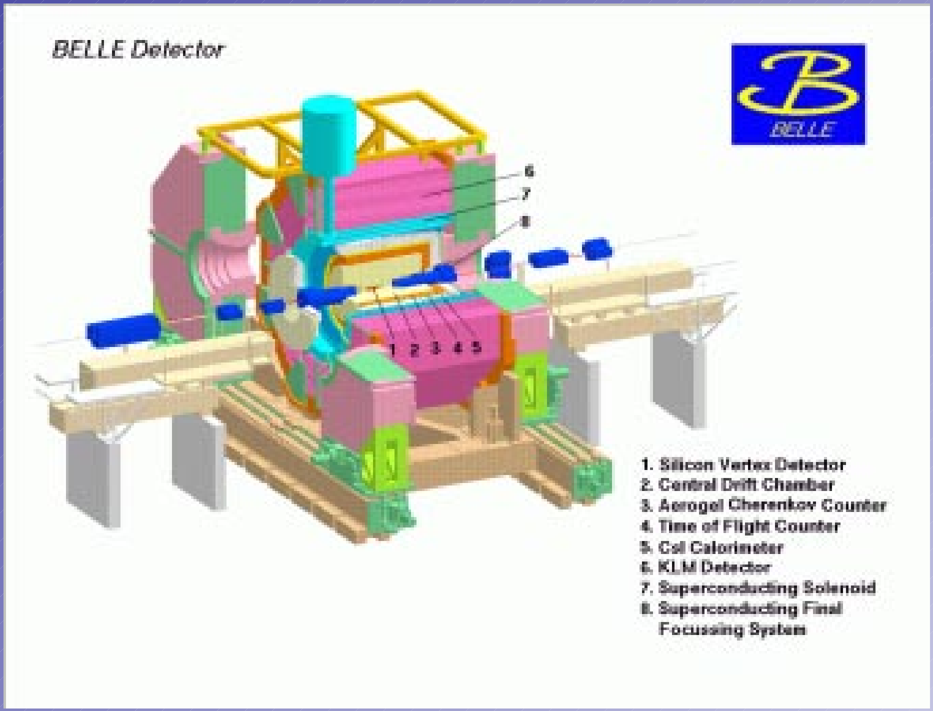
KEKB Accelerator



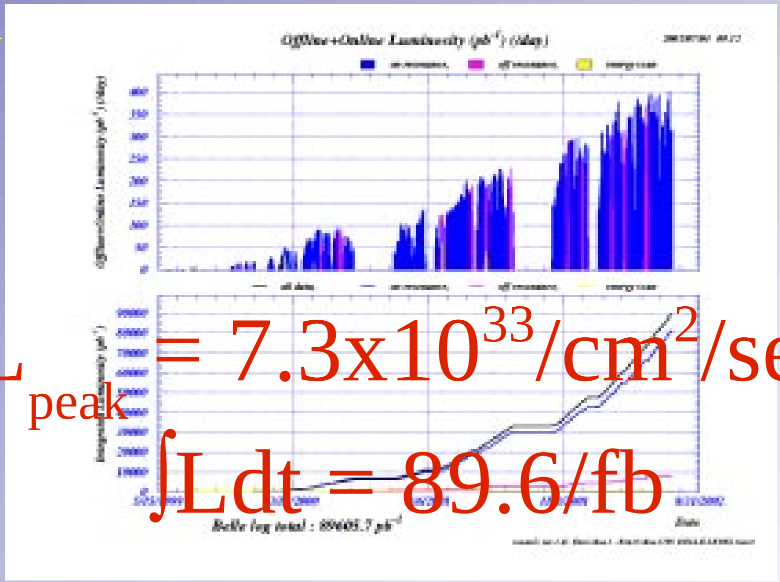
Asymmetric energy

$8.0(e^-) \times 3.5(e^+)$ GeV

Belle Detector



Luminosity



$L_{peak} = 7.3\text{x}10^{33}/\text{cm}^2/\text{sec}$

$\int L dt = 89.6/\text{fb}$

2. $B^0 \to J/\psi\, K^{*0}(K_S\pi^0)$

Integrated luminosity used for the analysis : $78\,fb^{-1}$

Event selection :

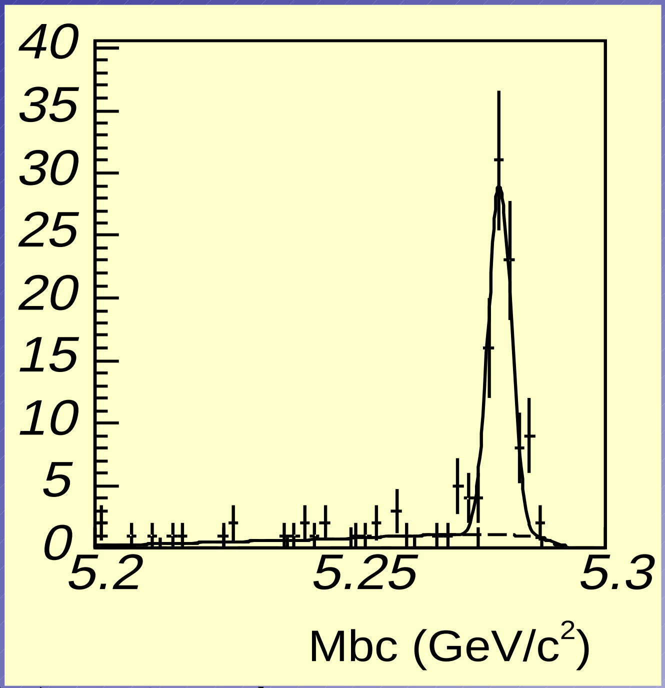
J/ψ : reconstructed using dilepton(e^+e^-, $\mu^+\mu^-$) decay.

K^* : $|M(K_S\pi^0) - M(K^{*0})| < 75 MeV/c^2$

B^0 : $5.27 < M_{bc} < 5.29\ GeV/c^2$

$-0.05 < \Delta E < 0.03\ GeV$

slow π^0 rejection : $\cos\theta_1$ (K* helicity angle) < 0.8



Mbc : invariant mass calculated assuming the energy to be beam energy

ΔE : difference between reconstructed B candidate and beam energy

→ 103 events remain

+ vertex quality selection

−>used for CP fit

* vertex reconstruction / flavor determination

→ covered by other talk

Time−dependent angular distribution

(Transversity basis)

$$\frac{d\Gamma}{d\cos\vartheta_{tr}\, d\phi\, d\cos\vartheta_{K*}\, d\Delta t} = \frac{9}{32\pi} \frac{e^{-|\Delta t|}/\tau_B}{2\tau_B} \sum_{i=1,6} f_i(\vartheta_{tr}, \phi, \vartheta_{K*})\, a_i(\Delta t)$$

$$f_1 = 2\cos^2\vartheta_{K*}(1-\sin^2\vartheta_{tr}\cos^2\phi) \qquad a_1 = |A_0^2|(1+\eta\, sin2\phi_1 \sin\Delta m \Delta t)$$

$$f_2 = \sin^2\vartheta_{K*}(1-\sin^2\vartheta_{tr}\sin^2\phi) \qquad a_2 = |A_{//}^2|(1+\eta\, sin2\phi_1 \sin\Delta m \Delta t)$$

$$f_3 = \sin^2\vartheta_{K*}\sin^2\vartheta_{tr} \qquad a_3 = |A_T^2|(1-\eta\, sin2\phi_1 \sin\Delta m \Delta t)$$

$$f_4 = \frac{-1}{\sqrt{2}} sin2\vartheta_{K*}\sin^2\vartheta_{tr}\, sin2\phi \qquad a_4 = \Re(A_{//}^* A_0)(1+\eta\, sin2\phi_1 \sin\Delta m \Delta t)$$

$$f_5 = \sin^2\vartheta_{K*}\, sin2\vartheta_{tr}\sin\phi \qquad a_5 = \eta\,\Im(A_{//}^* A_T)\cos\Delta m\Delta t - \eta\,\Re(A_{//}^* A_T)\, cos2\phi_1 \sin\Delta m \Delta t$$

$$f_6 = \frac{1}{\sqrt{2}} sin2\vartheta_{K*}\, sin2\vartheta_{tr}\cos\phi \qquad a_6 = \eta\,\Im(A_0^* A_T)\cos\Delta m\Delta t - \eta\,\Re(A_0^* A_T)\, cos2\phi_1 \sin\Delta m \Delta t$$

* A_0, $A_{//}$, A_T : helicity amplutudes
* Δm, τ_B : mixing parameter, B lifetime
* η : +1 for B^0, −1 for $\overline{B}^0$
* ϕ_1 : CP violating angle (β)

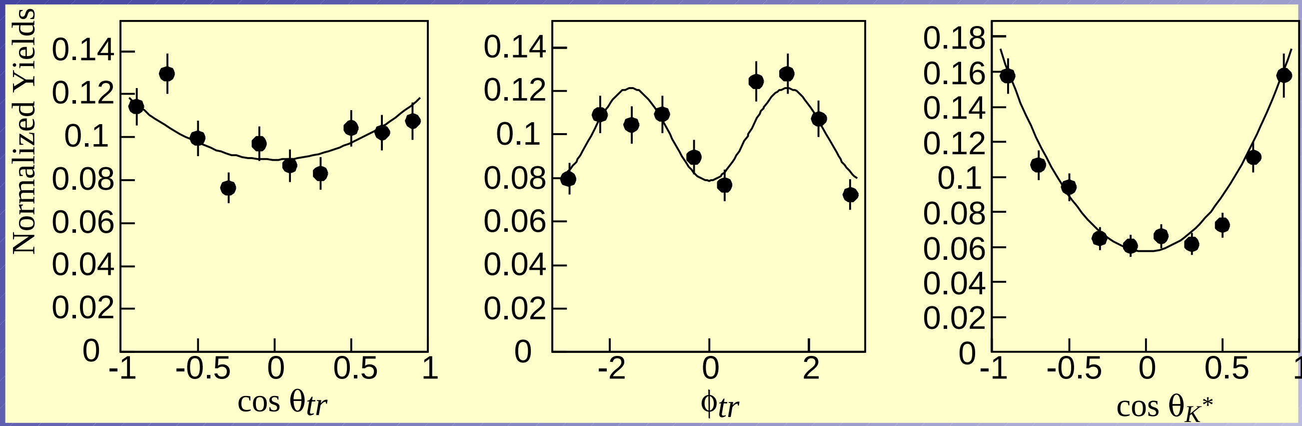
$\cos2\phi_1$ appears in interference terms! → useful to solve 2−fold ambiguity in $2\phi_1$ measured from $\sin2\phi_1$

Time−integrated angular analysis BELLE−CONF−0213(ABS701)

− A_0, $A_{//}$ and A_T can be determined by the fit to angular distributions only (time−integrated distributions).

− Non−CP decays ($B^0 \to J/\psi K^{*0}(K^+\pi^-)$, $B^+ \to J/\psi K^{*+}(K^+\pi^0, K_S\pi^+)$) are used (29.4/fb) ← * higher statistics than CP decay ($B^0 \to J/\psi K^*(K_S\pi^0)$)

* flavor determination is trivial



$|A_0|^2 + |A_{//}|^2 + |A_T|^2 = 1$
$\arg(A_0) = 0.0$

$|A_0|^2 = 0.62 \pm 0.02 \pm 0.03$
$|A_T|^2 = 0.19 \pm 0.02 \pm 0.03$
$\arg(A_{//}) = 2.83 \pm 0.19 \pm 0.08$
$\arg(A_T) = -0.09 \pm 0.13 \pm 0.06$

Free parameters:
$\sin 2\phi_1$ and $\cos 2\phi_1$

Probability Density Function (PDF) for CP fit

− Determination of sin $2\phi_1$ and $\cos 2\phi_1$ is done by the unbinned maximum likelihood fit to 3 transversity angles and Δt obtained event by event.

− PDF for the fit is constructed with following effects

1) Detector acceptance for angular distributions
   - as done for time−integrated analysis
   - parameterized 3D efficiency function obtained by MC

2) Background fractions and angular shapes
   - * feed across from other $J/\psi K^*$ subdecays
   - * non−resonant production of $B \to J/\psi + K + \pi$
   - * combinatorial background
     - − obtained from MC and M_{bc} sideband data
     - − angular shapes are parameterized in 3D polynomials.

3) Δt resolution of measurement

4) Wrong tagging effect

} treated in the same manner as those in Belle's standard CP analysis

$$PDF(M_{bc}, \vartheta_{tr}, \phi_{tr}, \vartheta_{K*}, \Delta t) = f_{sig}(M_{bc}) eff(\vartheta_{tr}, \phi_{tr}, \vartheta_{K*}) TADF(\vartheta_{tr}, \phi_{tr}, \vartheta_{K*}, \Delta t; \phi_1) + \sum_{BG\ sources} f_{bg}(M_{bc}) TADF_{BG}(\vartheta_{tr}, \phi_{tr}, \vartheta_{K*}, \Delta t)$$

Background TADF :

feed across : $e^{-|\Delta t|/\tau_B}/2\tau_B \times ADF_{fa}(\vartheta_{tr}, \phi_{tr}, \vartheta_{K*})$

non−resonant : $e^{-|\Delta t|/\tau_B}/2\tau_B \times ADF_{nr}(\vartheta_{tr}, \phi_{tr}, \vartheta_{K*})$

combinatorial : $\delta(\Delta t) \times ADF_{combi}(\vartheta_{tr}, \phi_{tr}, \vartheta_{K*})$

* η is replaced with $-q(1-2w)$ in signal TADF
(q = tagging flavor (±1), *w* = wrong tagging fraction)
* PDF is convoluted with proper resolution function for each term

Results

$$\sin 2\phi_1 = 0.13 \pm 0.51 \pm 0.06$$

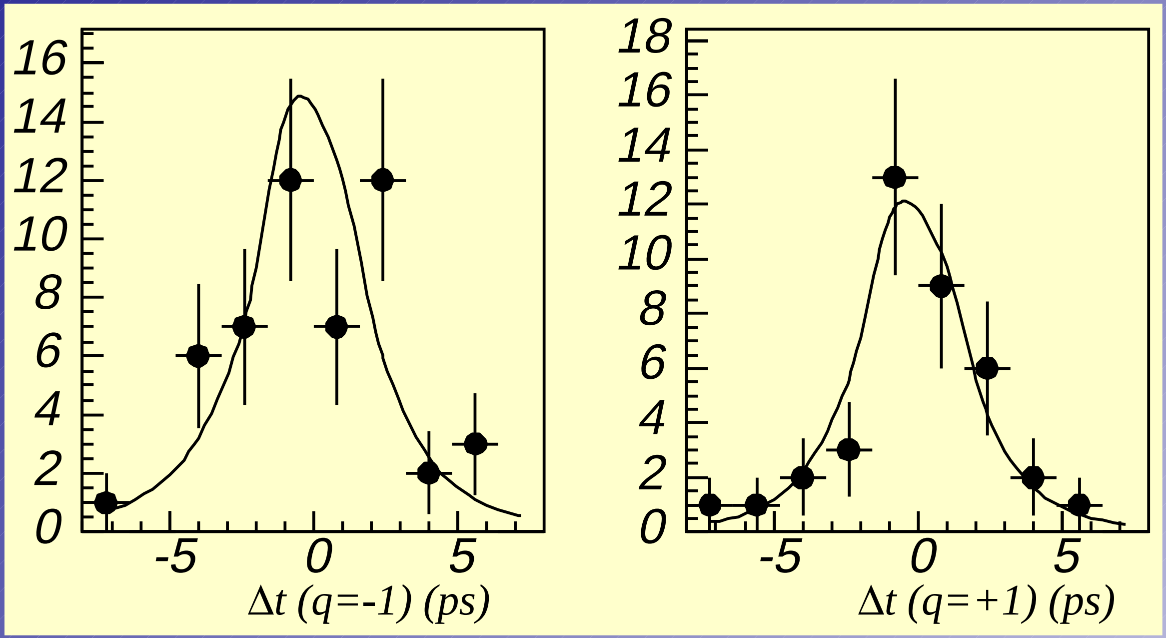
$$\cos 2\phi_1 = 1.40 \pm 1.28 \pm 0.19$$

c.f. 2D fit ($\cos\theta_{tr}$ only) : $\sin 2\phi_1 = 0.04 \pm 0.64$

Systematic error estimation

Item	$\delta\sin 2\phi_1$	$\delta\cos 2\phi_1$
Resolution parameters	±0.024	±0.092
Wrong tagging fractions	±0.019	±0.041
Helicity amplitudes	±0.042	±0.158
Background fraction	±0.012	±0.012
Angular shape for BG	±0.023	±0.034
Δt distribution for $\delta(t)$ BG	±0.009	±0.010
τ_B and Δm	±0.013	±0.011
Total	±0.06	±0.19

Δt distributions



Lines show the prediction by PDF with obtained CP parameter values

Discussion

− sign of $\cos 2\phi_1$

* 2−fold ambiguity in the choice in phases of helicity amplitudes (M.Suzuki, PRD 64, 117503)

1) $\phi_{\parallel} = 2.8$ rad., $\phi_{\perp} = -0.09$ rad. (s−quark helicity conserved)

$\rightarrow$ used to obtain shown values

2) $\phi_{\parallel} \rightarrow -\phi_{\parallel}$ and $\phi_{\perp} \rightarrow \pi - \phi_{\perp}$ (cannot exclude this)

$\rightarrow$ the sign of $\cos 2\phi_1$ flips while $\sin 2\phi_1$ does not change

$\cos 2\phi_1 = -1.31 \pm 1.28 \pm 0.19$

− Comparison with other measurements

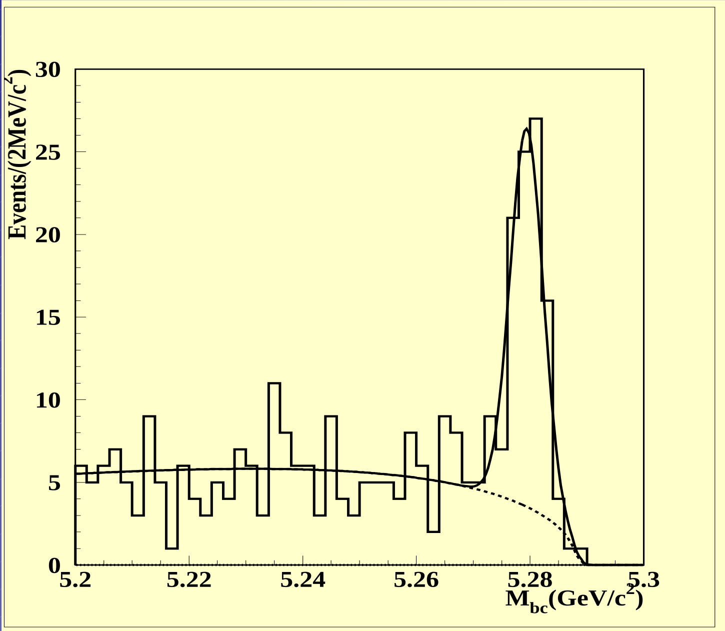
	$\sin 2\phi_1$	$\cos 2\phi_1$
BaBar	0.22 ± 0.52 (*1)	$+3.3\ (+0.6-1.0)\ (+0.6-0.7)$ (*2)
Belle	$0.13 \pm 0.51 \pm 0.06$	$+1.40 \pm 1.28 \pm 0.19$
	0.82 (fixed) (*3)	$+1.02 \pm 1.16$

(*1) hep−ex/0207042, (*2) obtained in global CP fit, hep−ex/0203007, (*3) value shown at Moriond conf.

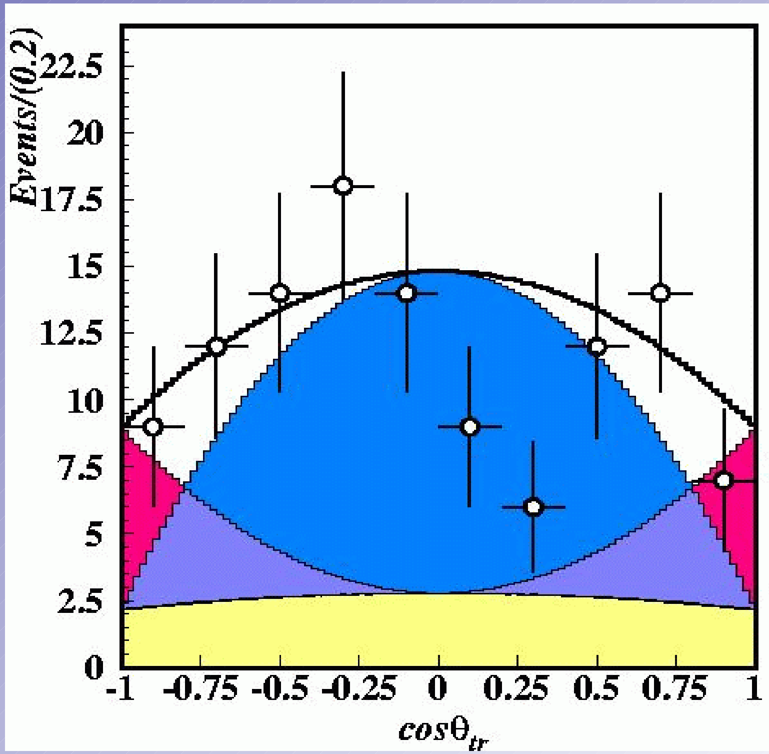
3. Other channels

– Time−dependent analysis is still in preparation for following modes.
– Status of time−integrated analysis is discussed

a) $B \to D^{*+} D^{*-}$ (for sin $2\phi_1$ determination)



$$\frac{d\Gamma}{d\cos\vartheta_{tr}} = \frac{3}{4}(1-R_T)\sin^2\vartheta_{tr} + \frac{3}{2}R_T\cos^2\vartheta_{tr}$$



$Br(B \to D^{*+} D^{*-}) = (\,7.6 \pm 0.9 \pm 1.4\,) \times 10^{-4}$

(with $78 fb^{-1}$)

b) $B \to D^{*}\rho$ (for $\sin(2\phi_1+\phi_3)$ determination)

− Fit to projected helicity angles

→ Transversity amplitudes with imaginary parts

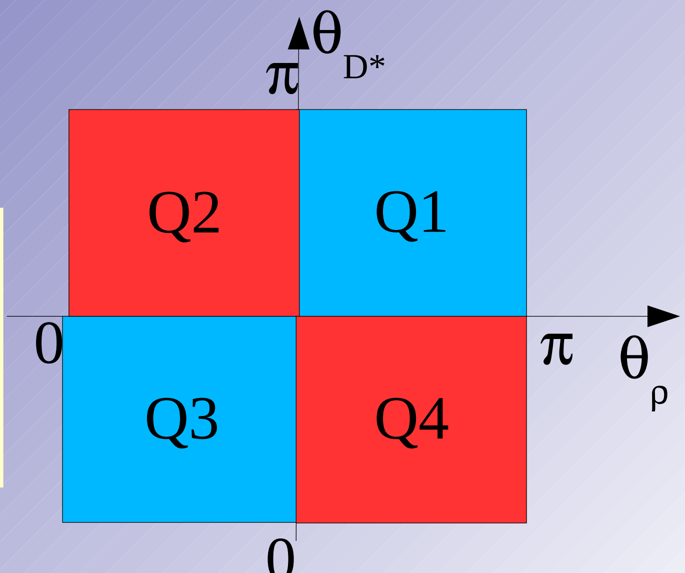
$$\frac{d\Gamma}{d\cos\vartheta_i} = \frac{4\pi}{3}|A_0|^2\cos^2\vartheta_i + \frac{2\pi}{3}(|A_T|^2+|A_{//}|^2)\sin^2\vartheta_i$$

$$\frac{d\Gamma}{d\phi} = (\frac{4}{9}|A_0|^2+\frac{8}{9}|A_T|^2)\sin^2\phi + (\frac{4}{9}|A_0|^2+\frac{8}{9}|A_{//}|^2)\cos^2\phi$$

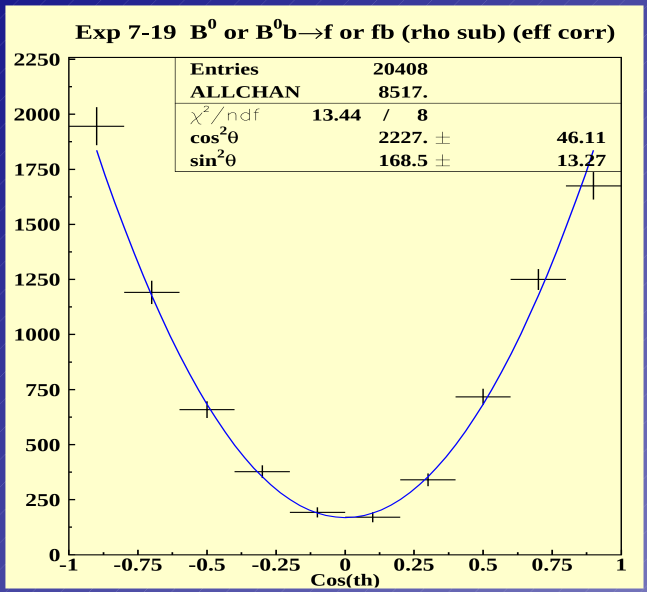
Interference components appears in "half projected" angular distribution

$$\Delta = (Q1+Q3)-(Q2+Q4)$$

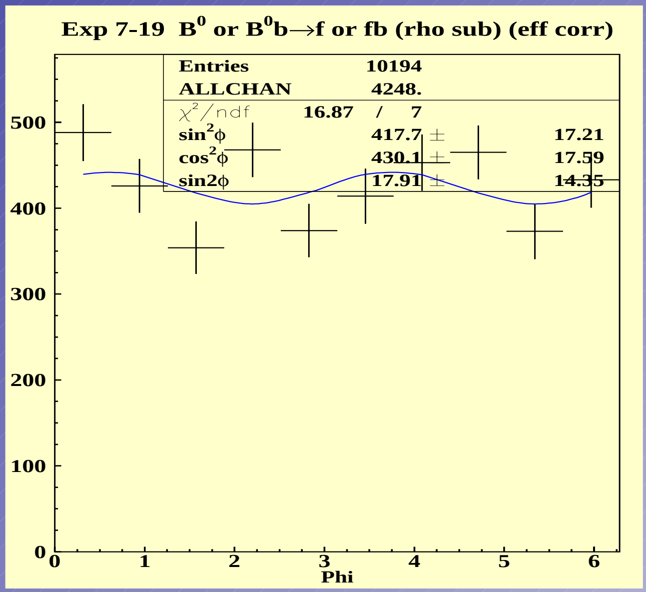
$$\frac{d\Delta}{d\phi} = \frac{-8}{9\sqrt{2}}\Im(A_0^* A_T)\sin\phi + \frac{8}{9\sqrt{2}}\Re(A_0^* A_{//})\cos\phi$$



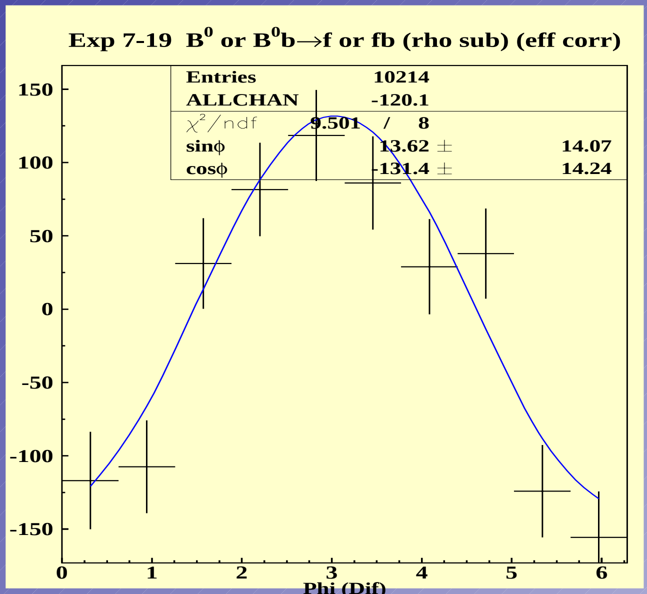
$\cos\theta_1 + \cos\theta_2$



χ

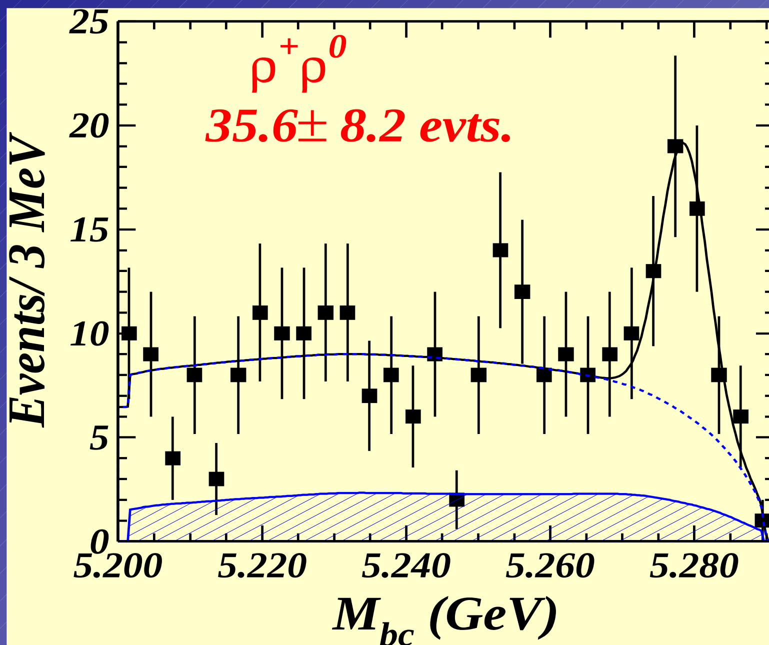


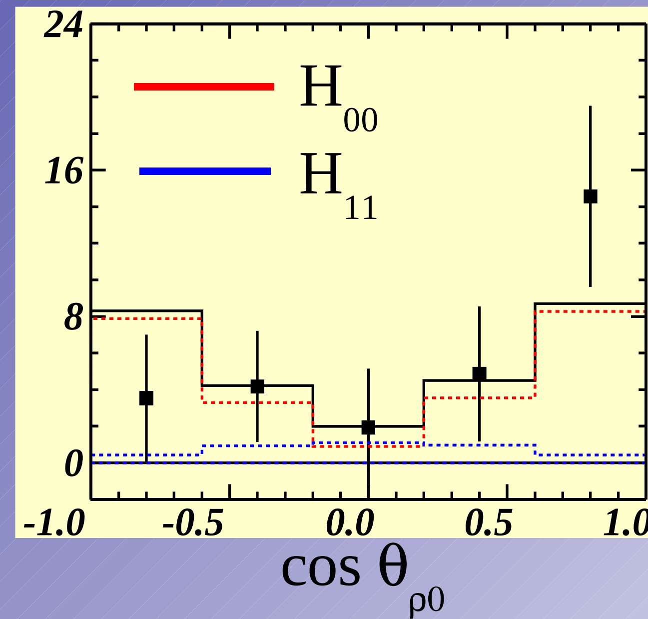
Δ

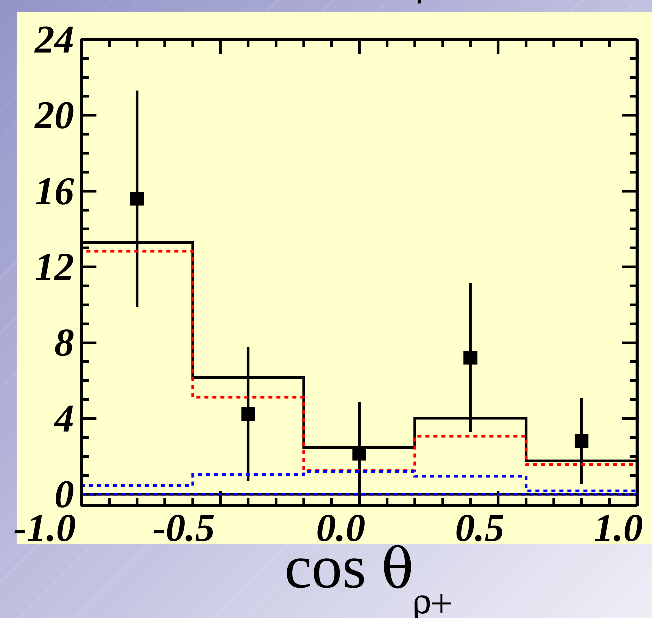


Helicity amplitudes for $B \to D^* \rho$ will be determined soon.

c) $B^{+} \to \rho^{+}\rho^{0}$ − Detail is covered by other talk (A.Gordon in HQ−3)







$$1 - \frac{\Gamma_T}{\Gamma} = 0.92 \pm 0.61$$

5. Summary

- Full time−dependent angular analysis is performed for $B \to J/\psi K^*$ decays collected with Belle detector at KEK B−factory.

- CP violation parameters $\sin 2\phi_1$ and $\cos 2\phi_1$ are determined to be

$$\sin 2\phi_1 = +0.13 \pm 0.51 \pm 0.06$$

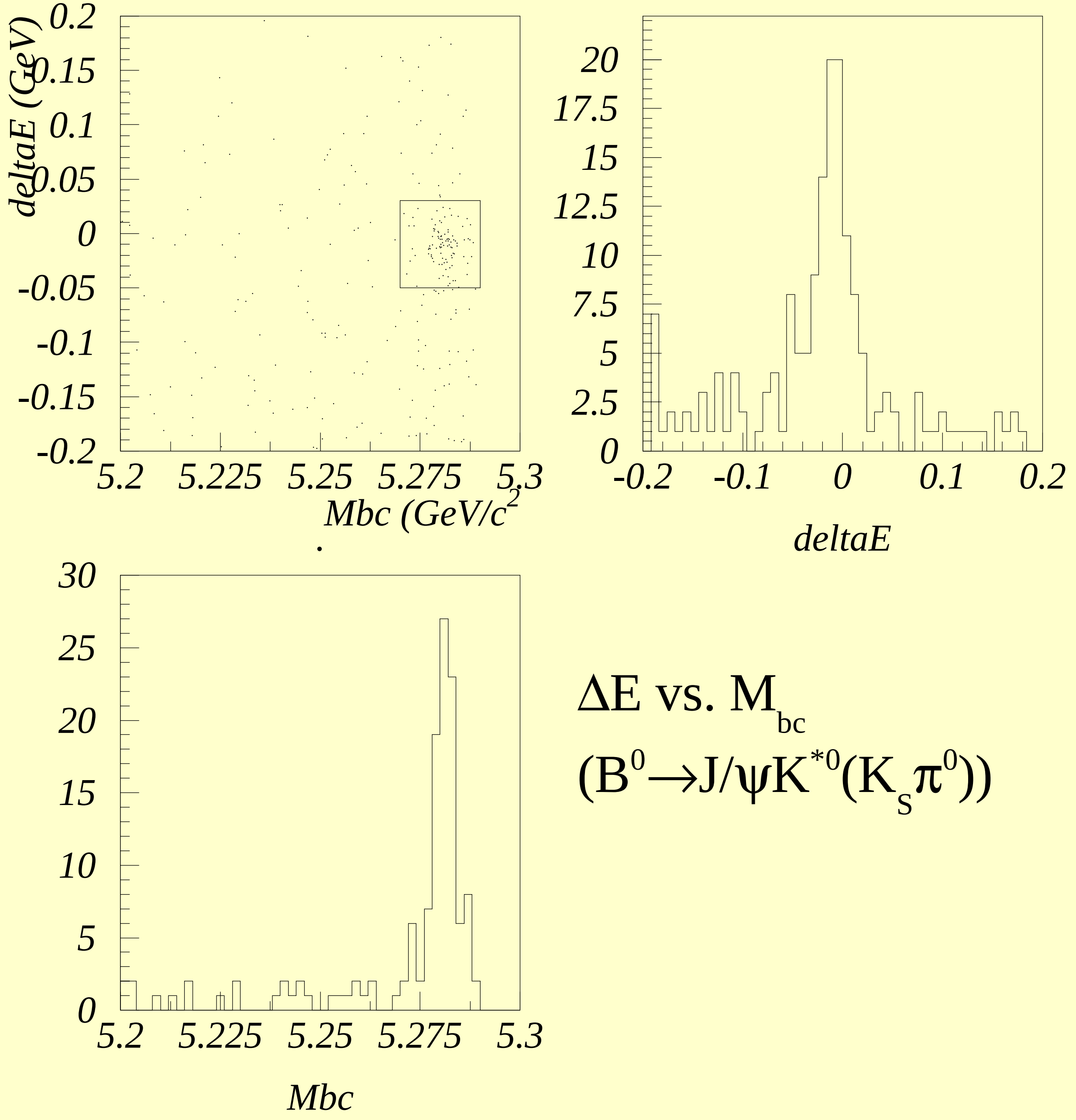
$$\cos 2\phi_1 = +1.40 \pm 1.28 \pm 0.19$$

- When fixing $\sin 2\phi_1 = +0.82$, $\cos 2\phi_1 = +1.02 \pm 1.16$

- Taking s−quark helicity conservation choice of amplitude phases, obtained sign of $\cos 2\phi_1$ prefers $2\phi_1 = 55^o$ with $\sin 2\phi_1 = +0.82$ (namely, choice of $2\phi_1 = 145^o$ is not prefered) although statistical error is still too large.

- The angular analysis for other modes are in progress.

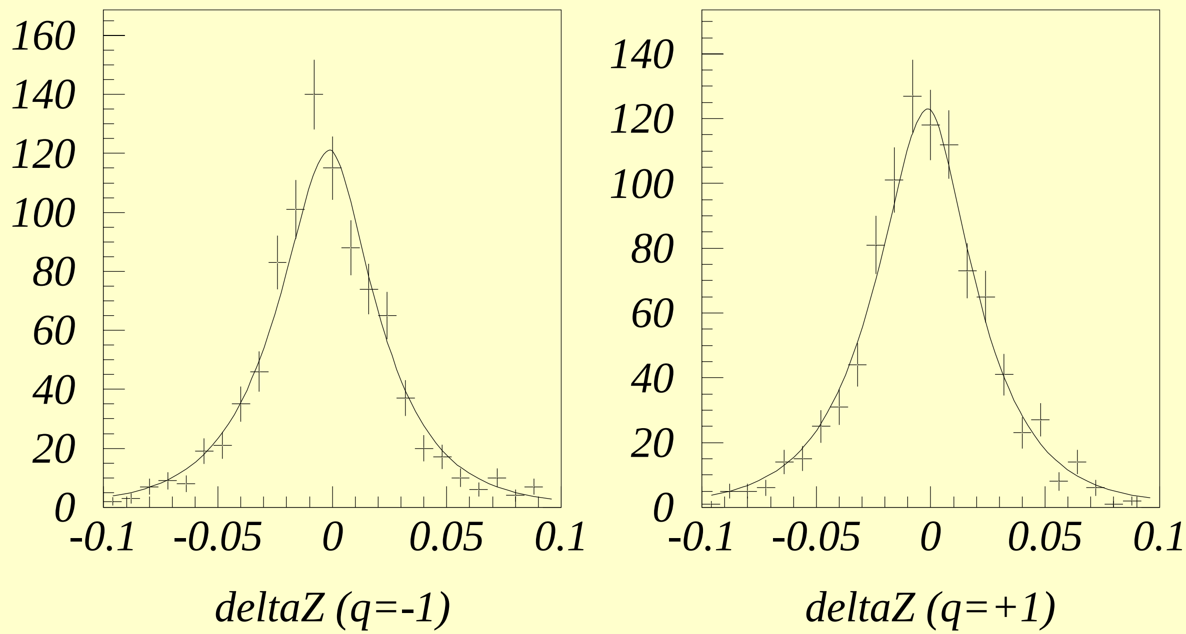
Backup Slides



ΔE vs. M_{bc}

$(B^0 \rightarrow J/\psi K^{*0}(K_S \pi^0))$

Δz distributions for J/ψK*($K^+\pi^-$); selftag



Lines show the prediction by PDF with $\sin 2\phi_1 = \cos 2\phi_1 = 0.0$

Fit toJ/ψK*($K^+\pi^-$)

"sin 2f1" = 0.04 ± 0.14
"cos 2f1" = 0.27 ± 0.32
−> consistent with 0
c.f. selftag
"sin2f1" = 0.00 ± 0.07
"cos2f1" = −0.01 ± 0.18

Linearity check

Case I:

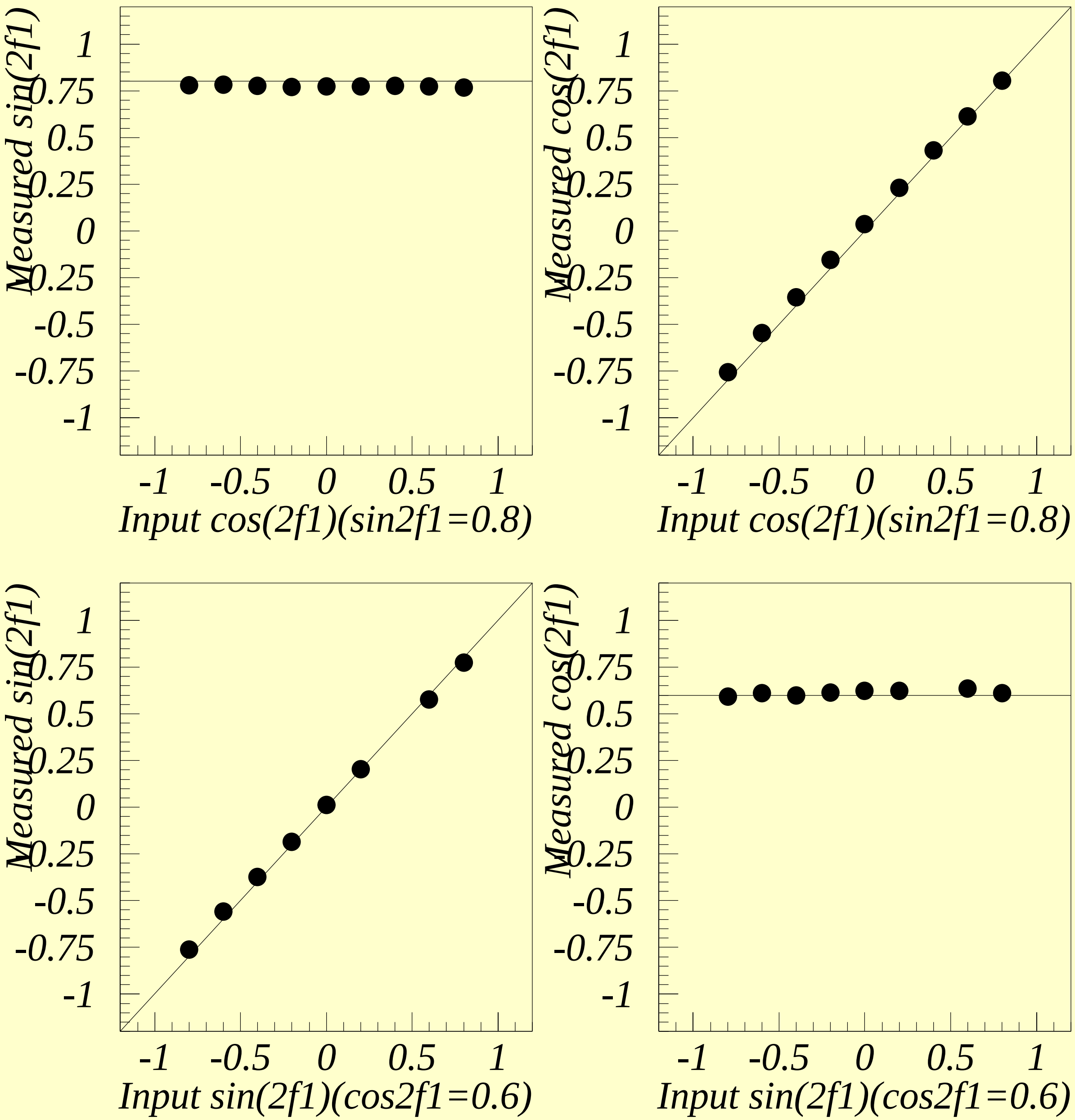
$\sin 2\phi_1 = 0.8$ fixed

scan $\cos 2\phi_1$

Case II:

$\cos 2\phi_1 = 0.6$ fixed

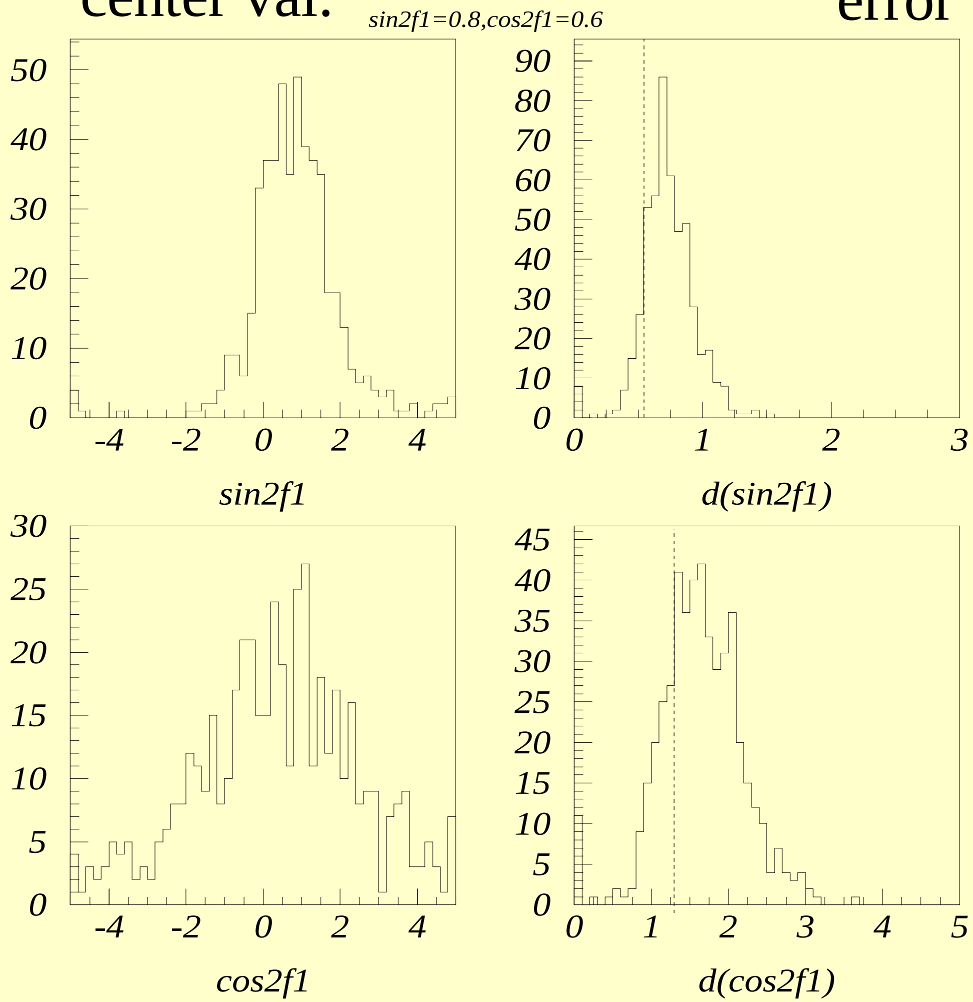
scan $\sin 2\phi_1$



Ensemble test

- 500 sets of samples with 100 events are fitted and the distributions of output are checked. (Input: $\sin 2\phi_1$ = 0.8, $\cos 2\phi_1$=0.6)

center val. error

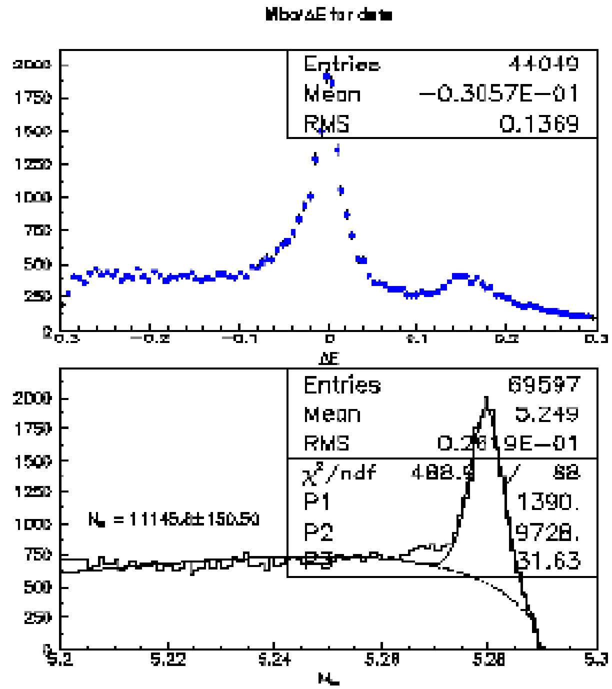


$\sin 2\phi_1$

$\cos 2\phi_1$

$\Delta E/M_{bc}$ for data

- with $M_{bc} < 5.27 GeV/c^2$
- -100 < ΔE < 50 MeV :



Argus function doesn't describe the background for $M_{bc} < 5.27 GeV/c^2$
(behaviour expected for such hadronic B decays)