Measurements of $\phi_2(\alpha)$ and $\phi_3(\gamma)$ at Belle

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For the Belle Collaboration

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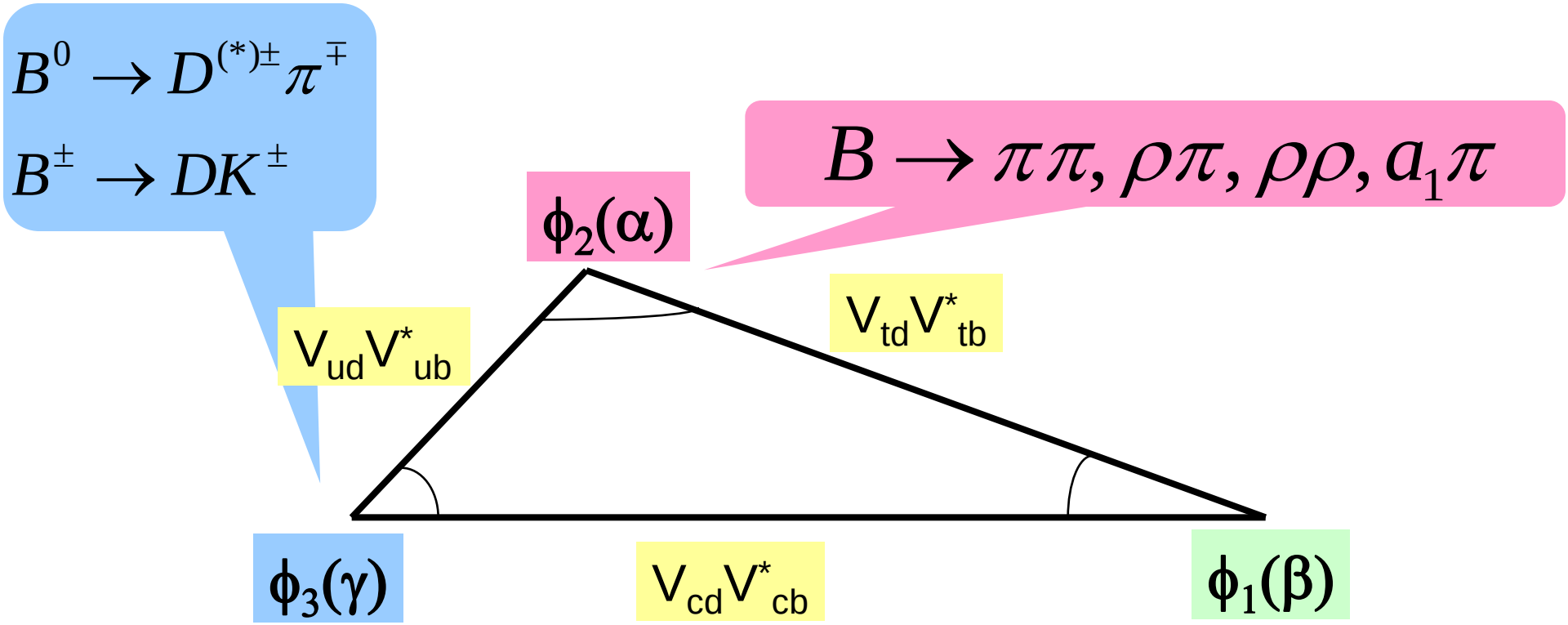
Outline

- Introduction
- $\phi_2(\alpha)$ Measurements
  - $B \to \pi\pi$
  - $B \to \rho\rho$
  - $B \to \rho\pi$
  - $B \to a_1\pi$ (B.R.)
- $\phi_3(\gamma)$ Measurements
  - the GLW method: $B^{\pm} \to D_{CP}^{(*)} K^{\pm}$
  - the ADS method: $B^{\pm} \to [K^{\mp}\pi^{\pm}]_D K$
  - Dalitz plot analysis: $B^{\pm} \to D^{(*)} K^{(*)\pm}$, $D^0 \to K_S\pi^+\pi^-$
  - time-dependent CPV: $B^0 \to D^{(*)-}\pi^+$
- Summary

Introduction

Unitarity Triangle

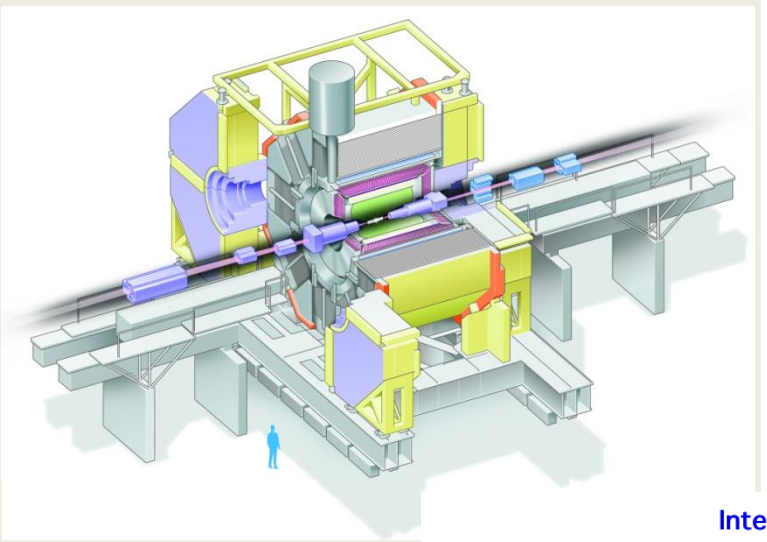
Unitarity of the CKM matrix $\rightarrow$ $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



Introduction

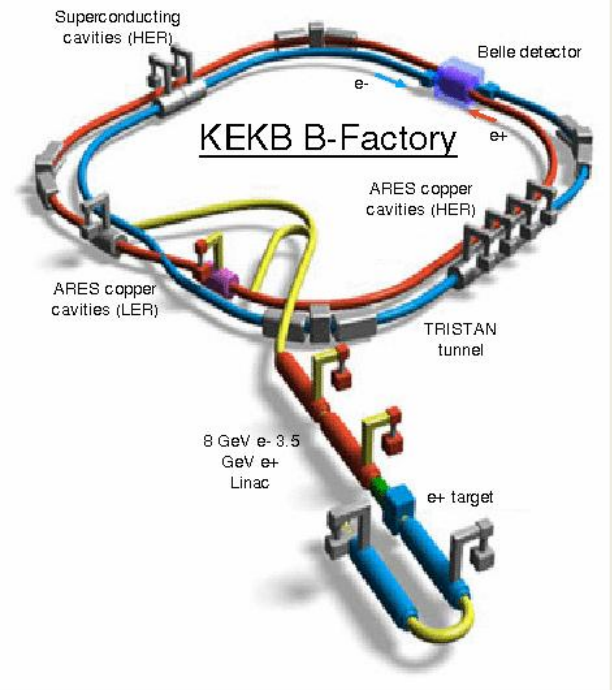
Belle & KEKB

~400 collaborators



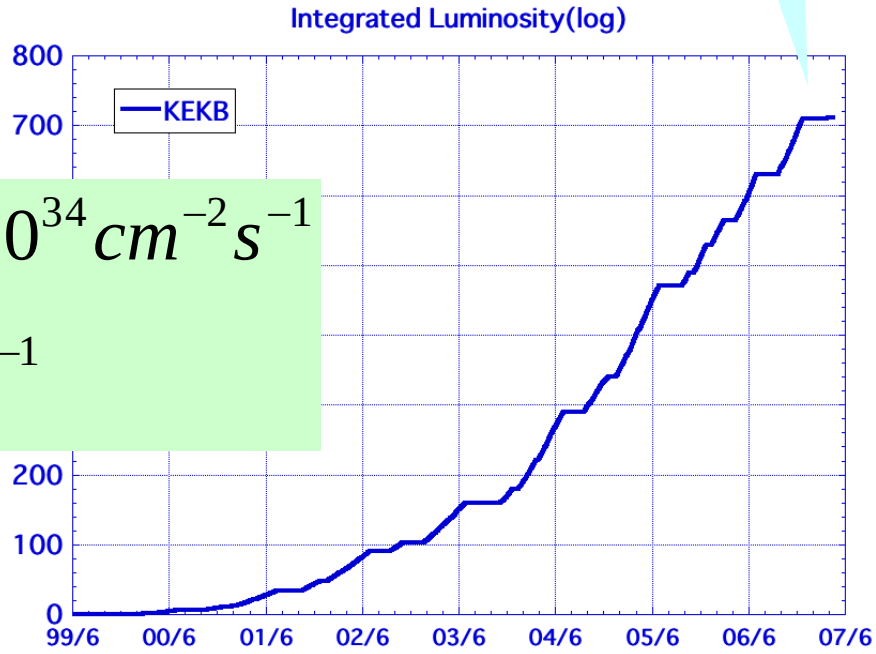
Crab cavity installed!

8GeV (e^-) × 3.5GeV (e+)



$$L_{peak} = 1.71 \times 10^{34} cm^{-2} s^{-1}$$

$$\int L dt = 710\, fb^{-1}$$



PRL 98, 211801 (2007)

BELLE

$535 MB\bar{B}$

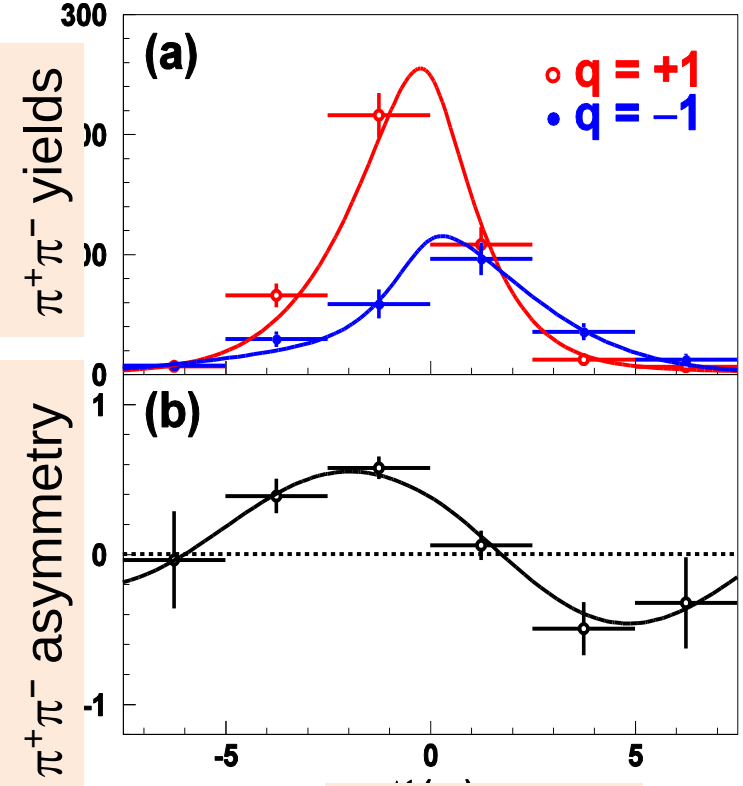
$\phi_2(\alpha)$ Measurement

$B \to \pi\pi$

$$A_{\pi\pi} = +0.55 \pm 0.08(stat.) \pm 0.05(syst.)$$

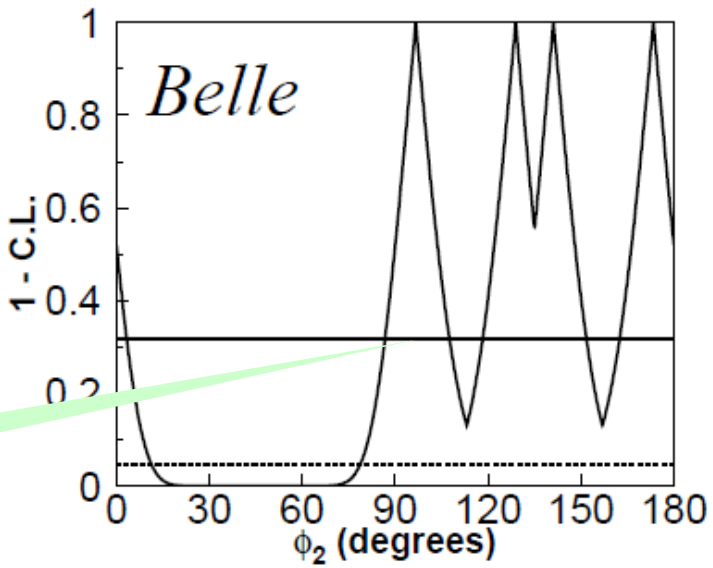
$$S_{\pi\pi} = -0.61 \pm 0.10(stat.) \pm 0.04(syst.)$$

$$S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}^2}\,\sin(2\phi_2 + 2\theta)$$



Isospin relation
WA
BR($\pi^+\pi^-$)
BR($\pi^+\pi^0$)
BR($\pi^0\pi^0$)
$A_{cp}(\pi^0\pi^0)$

Direct CPV @ 5.5σ



97° ± 11°

$\phi_2(\alpha)$ Measurement

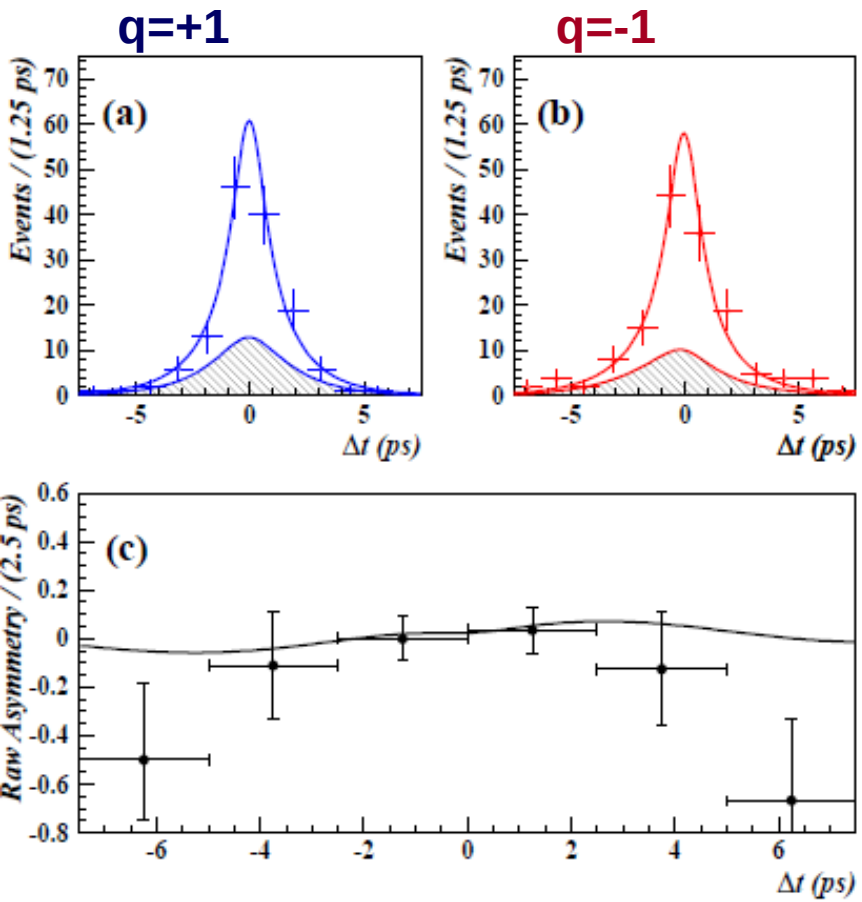
$B \to \rho\rho$

535$MB\bar{B}$

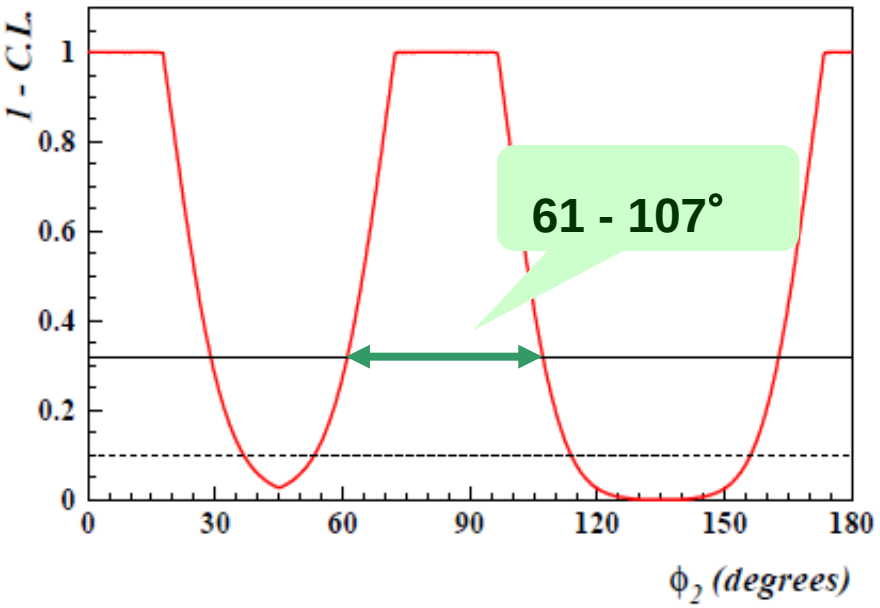
PRD76, 011104(R) (2007)

$$A_{\rho\rho} = +0.16 \pm 0.21(stat) \pm 0.07(syst)$$

$$S_{\rho\rho} = +0.19 \pm 0.30(stat) \pm 0.07(syst)$$



Isospin relation WA
BR($\rho^+\rho^-$), BR($\rho^+\rho^0$), BR($\rho^0\rho^0$)
~~$A_{cp}(\rho^0\rho^0)$~~



PRL 98, 221602 (2007)

BELLE

$449 M B\bar{B}$

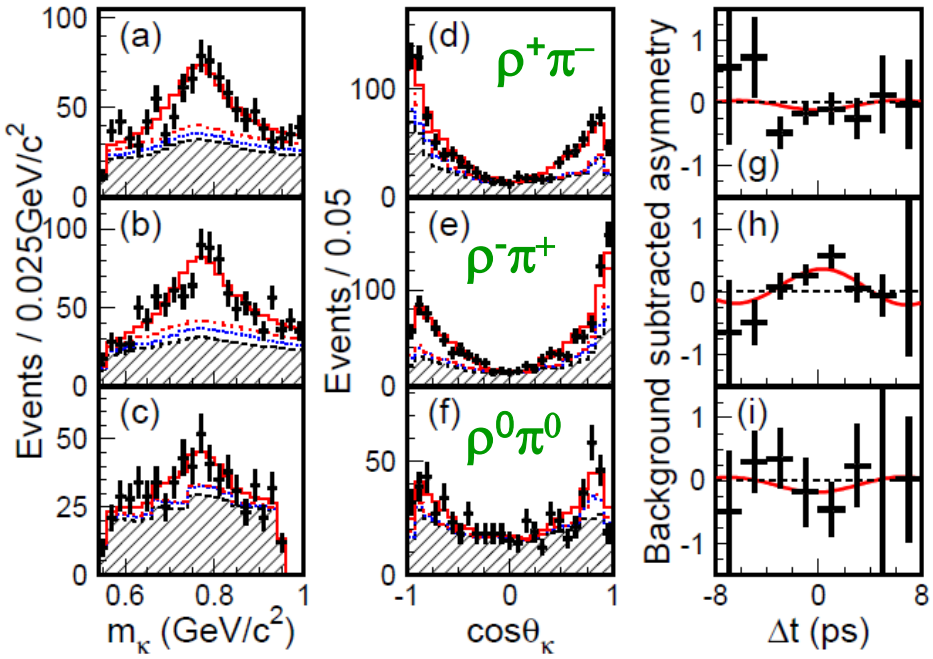
$\phi_2(\alpha)$ Measurement

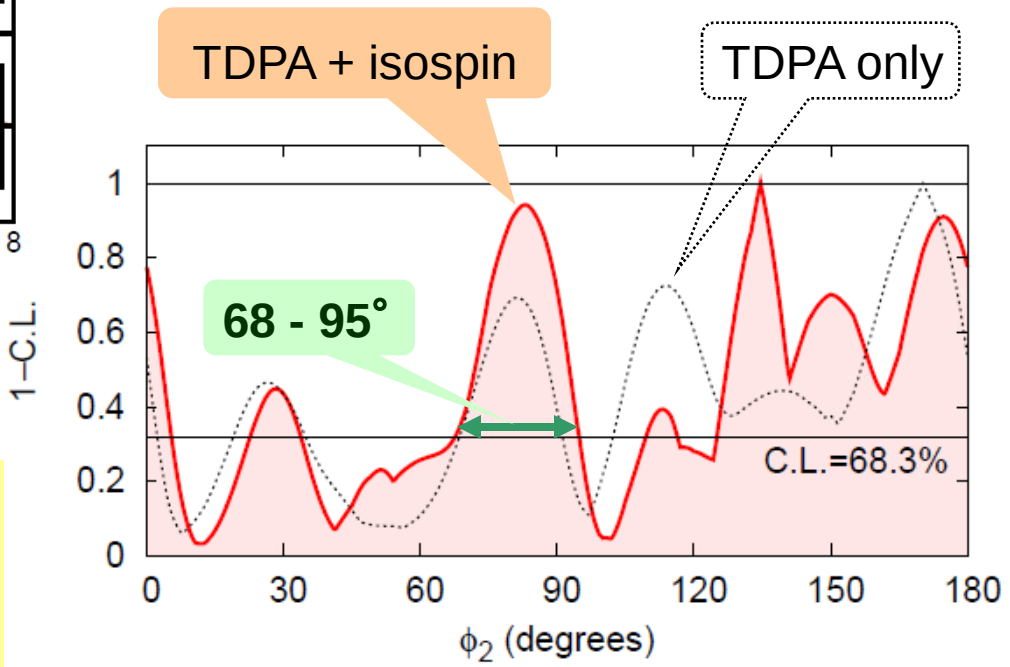
$B^0 \to (\rho\pi)^0$

Time-dependent Dalitz Plot Analysis (TDPA)

A = complex amplitudes of $B^0 \to \rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0$

$$e^{+2i\phi 2} = \frac{\bar{A}^+ + \bar{A}^- + 2\bar{A}^0}{A^+ + A^- + 2A^0}$$





$$A_{\rho^0\pi^0} = -0.45 \pm 0.35(stat) \pm 0.32(syst)$$

$$S_{\rho^0\pi^0} = +0.15 \pm 0.57(stat) \pm 0.43(syst)$$

B.R. Measurement

$B \to a_1\pi$

535$M B\bar{B}$

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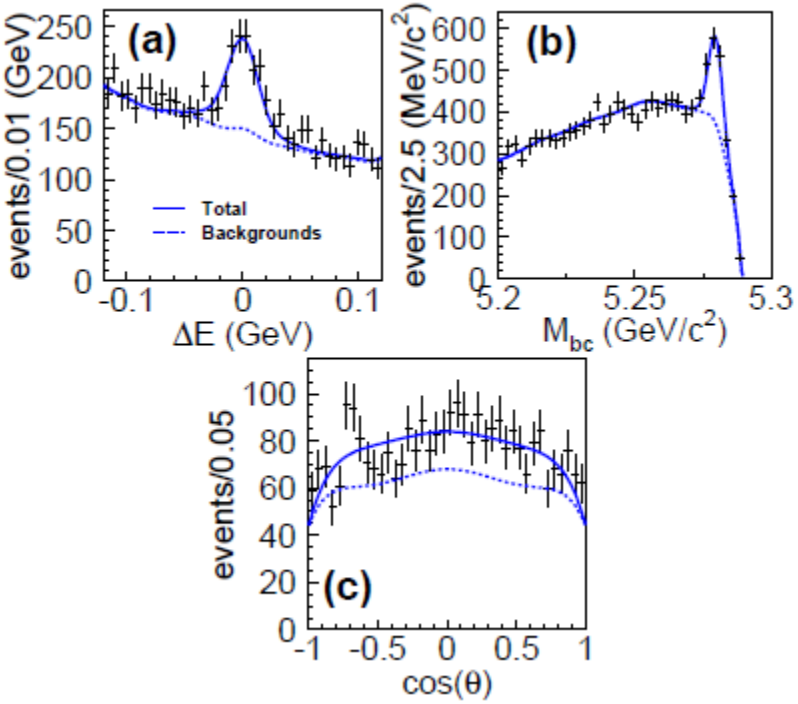
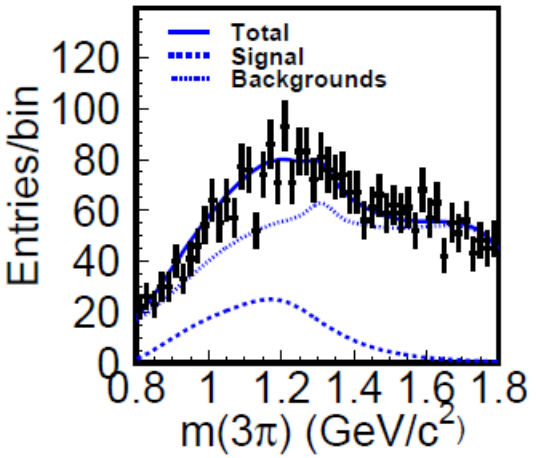




$$B.R.(B^0 \to a_1^{\pm}\pi^{\mp})B.R.(a_1 \to \pi^{\pm}\pi^{\pm}\pi^{\mp})$$
$$= (14.9 \pm 1.6 \pm 2.3) \times 10^{-6}$$

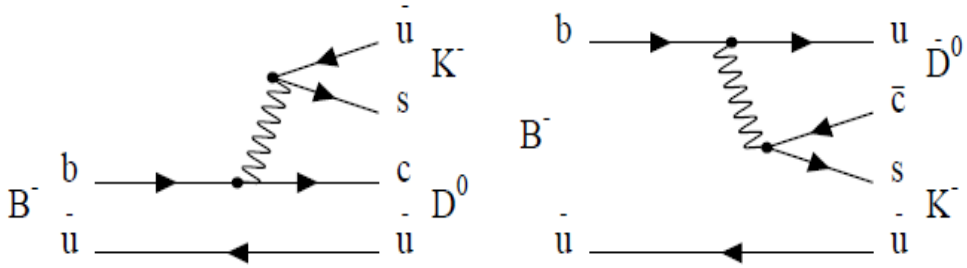
Gronau, Zupan
PRD 73, 057502(2006)

$\phi_3(\gamma)$ Measurements

GLW method

PRD73, 051106 (R)(2006)

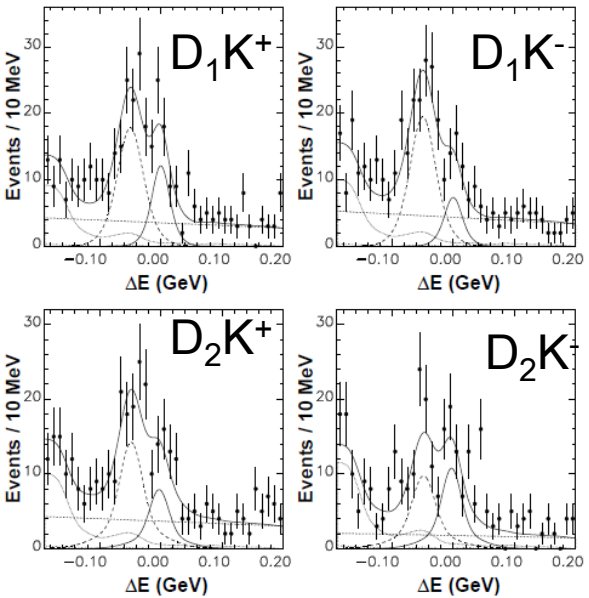
Gronau, London (1991)
Gronau, Wyler (1990)



$$\mathcal{A}_{1,2} \equiv \frac{\mathcal{B}(B^- \to D_{1,2}K^-) - \mathcal{B}(B^+ \to D_{1,2}K^+)}{\mathcal{B}(B^- \to D_{1,2}K^-) + \mathcal{B}(B^+ \to D_{1,2}K^+)} = \frac{2r\sin\delta'\sin\phi_3}{1 + r^2 + 2r\cos\delta'\cos\phi_3}$$

CP-even: $D_1 = K^+K^-, \pi^+\pi^-$

CP-odd: $D_2 = K_S\pi^0, K_S\omega, K_S\phi$



$B \to D_{1,2}K$

$$A_1 = +0.06 \pm 0.14(stat) \pm 0.05(syst)$$
$$A_2 = -0.12 \pm 0.14(stat) \pm 0.05(syst)$$

$B \to D^*_{1,2}K$

$$A^*_1 = -0.20 \pm 0.22(stat) \pm 0.04(syst)$$
$$A^*_2 = +0.13 \pm 0.30(stat) \pm 0.08(syst)$$

➔ **Weak constraint on ϕ_3**

$\phi_3(\gamma)$ Measurements

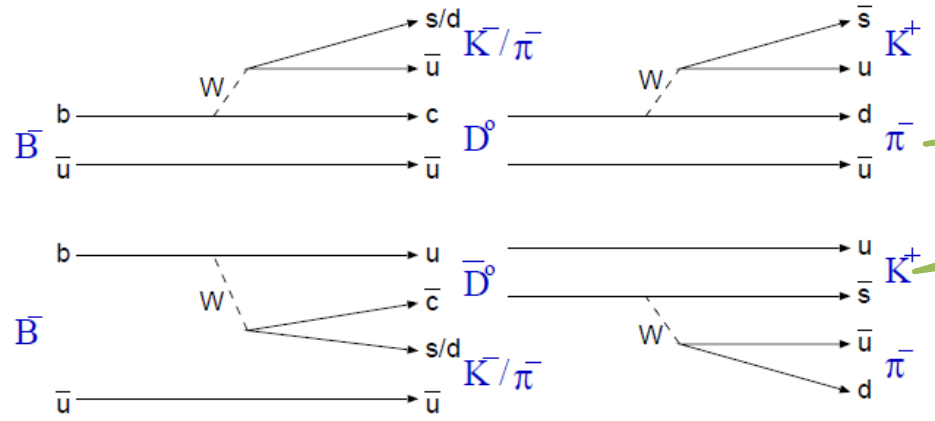
ADS method

388$M B\bar{B}$

hep-ex/0508048

Atwood, Danietz, Soni (1997)

CP violation effects enhanced , when the interfering amplitudes are comparable.



Color-allowed + Cabbibo suppressed

Color-suppressed + Cabbibo allowed

$$\mathcal{R}_{DK} = \frac{Br(B \to D_{\text{supp}} K)}{Br(B \to D_{\text{fav}} K)} = r_B^2 + r_D^2 + 2 r_B r_D \cos\varphi_3 \cos\delta$$

$$R_{DK} = (0.0^{+8.4}_{-7.9}(stat) \pm 1.0(syst)) \times 10^{-3}$$

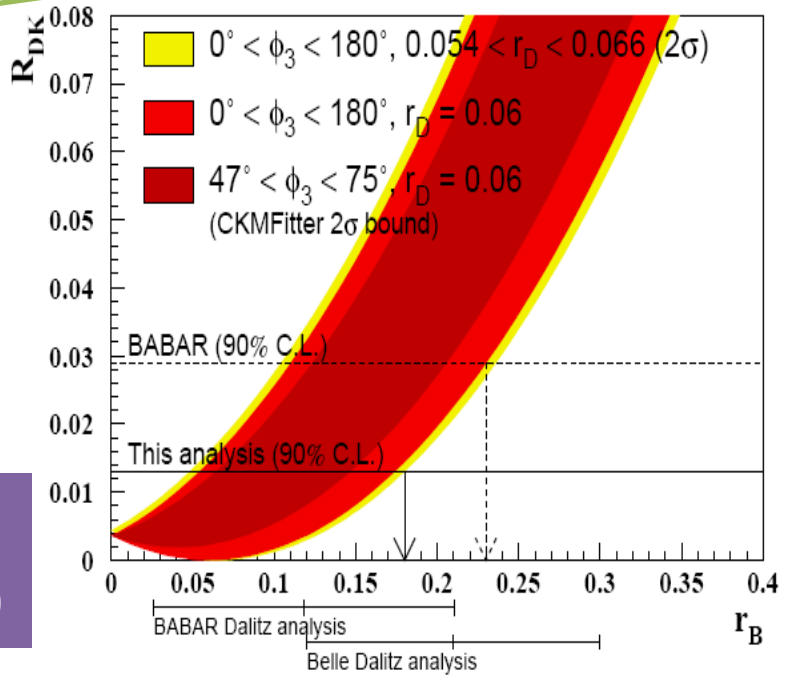
$$< 0.014 \,(\text{at } 90\%\,\text{C.L.})$$

$$r_B \equiv \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|,$$

$$\mathcal{A}_{D\pi} \equiv \frac{\mathcal{B}(B^- \to D_{\text{sup}}\pi^-) - \mathcal{B}(B^+ \to D_{\text{sup}}\pi^+)}{\mathcal{B}(B^- \to D_{\text{sup}}\pi^-) + \mathcal{B}(B^+ \to D_{\text{sup}}\pi^+)}.$$

$$\mathcal{A}_{D\pi} = 0.10 \pm 0.22\,(\text{stat}) \pm 0.02\,(\text{syst}),$$

$r_B < 0.18$ (90% C.L.)



$\phi_3(\gamma)$ Measurements

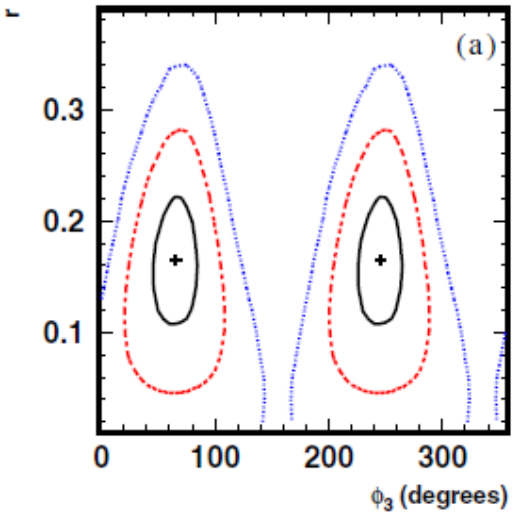
Dalitz plot method

BELLE

$388 M B\bar{B}$

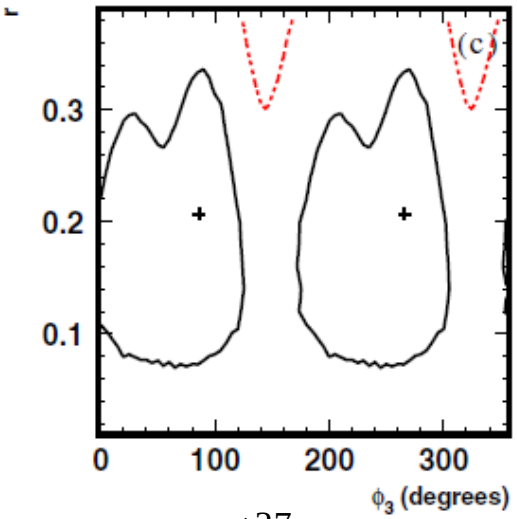
PRD73, 112009 (2006)

$B^{\pm} \to DK^{\pm}$



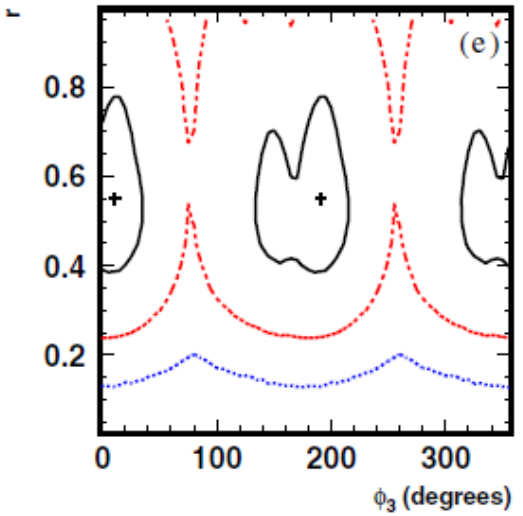
$\phi_3 = 66^{+19}_{-20}(\text{stat.})$

$B^{\pm} \to D^{*}K^{\pm} \to D\pi^0 K^{\pm}$



$\phi_3 = 86^{+37}_{-93}(\text{stat.})$

$B^{\pm} \to DK^{*\pm} \to DK_s^0\pi^{\pm}$



$\phi_3 = 11^{+23}_{-57}(\text{stat.})$

$$\phi_3 = 53^{\circ\,+15^{\circ}}_{-18^{\circ}}(\text{stat.}) \pm 3^{\circ}(\text{syst.}) \pm 9^{\circ}(\text{model})$$

$$r_B = 0.16^{+0.05}_{-0.05}(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.05(\text{model})$$

$$M(B^{\pm} \to D^0(\bar{D}^0)K^{\pm} \to K_S\pi^+\pi^-K^{\pm})$$
$$= f(m_{\pm}^2, m_{\mp}^2) + re^{i\delta \pm i\phi_3} f(m_{\mp}^2, m_{\pm}^2)$$

Giri, Grossman, Soffer, Zupan (2003)

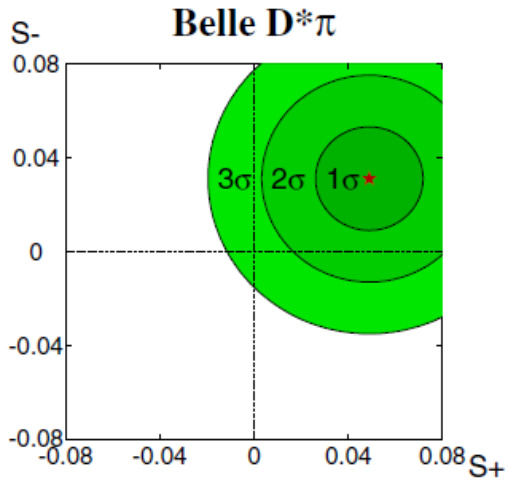
PRD73, 092003 (2006)

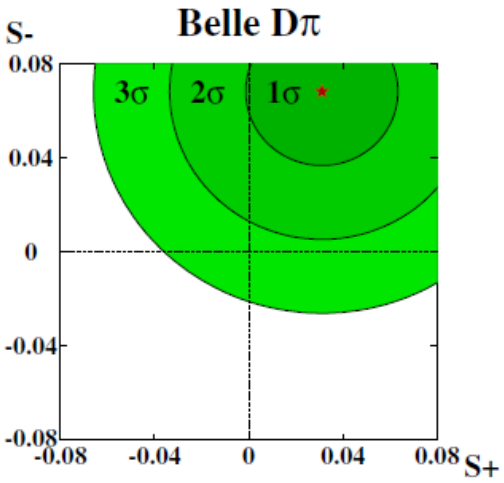
BELLE

$388 M B\bar{B}$

$\phi_3(\gamma)$ Measurements

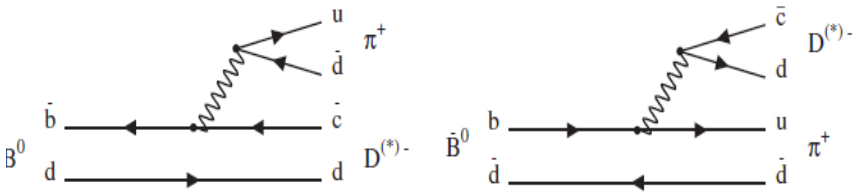
tCPV method



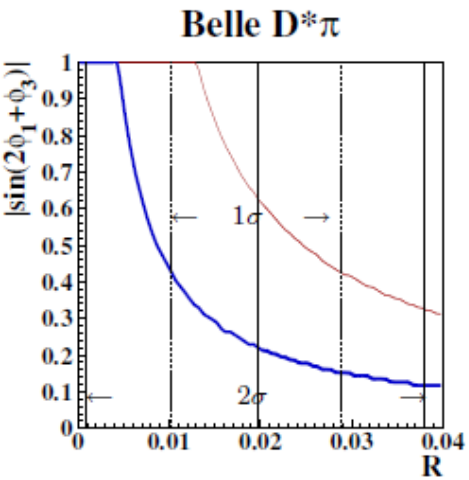


CFD

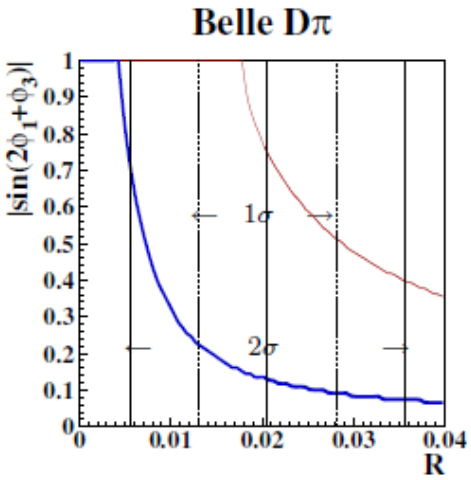
DCSD



$$S_{\pm} = \frac{2(-1)^L R \sin(2\phi_1 + \phi_3 \pm \delta)}{1 + R^2}$$



$|\sin(2\phi_1 + \phi_3)| > 0.44(0.13)$
at 68% (95%)CL



$|\sin(2\phi_1 + \phi_3)| > 0.52(0.07)$
at 68% (95%)CL

factorizat ion,
SU(3),
$BR(B \to D_s^{*}\pi)$,
lattice QCD calc

for $D^{*}\pi$

$|\sin(2\phi_1 + \phi_3)| > 0.44$

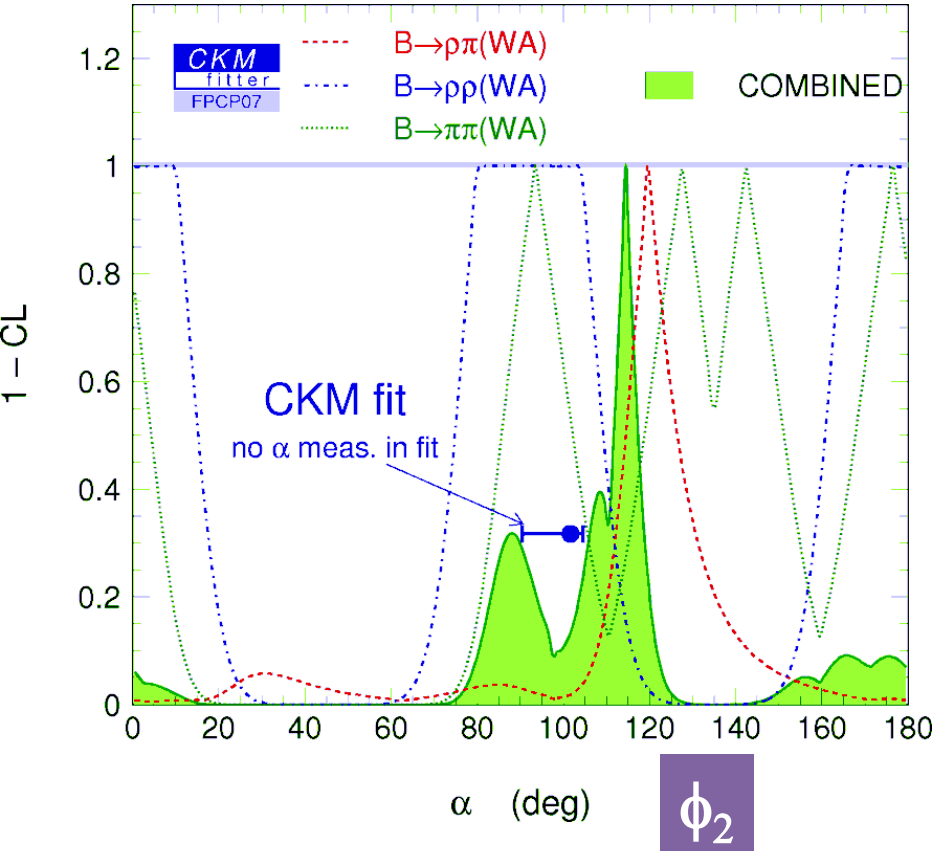
for $D\pi$

$|\sin(2\phi_1 + \phi_3)| > 0.52$

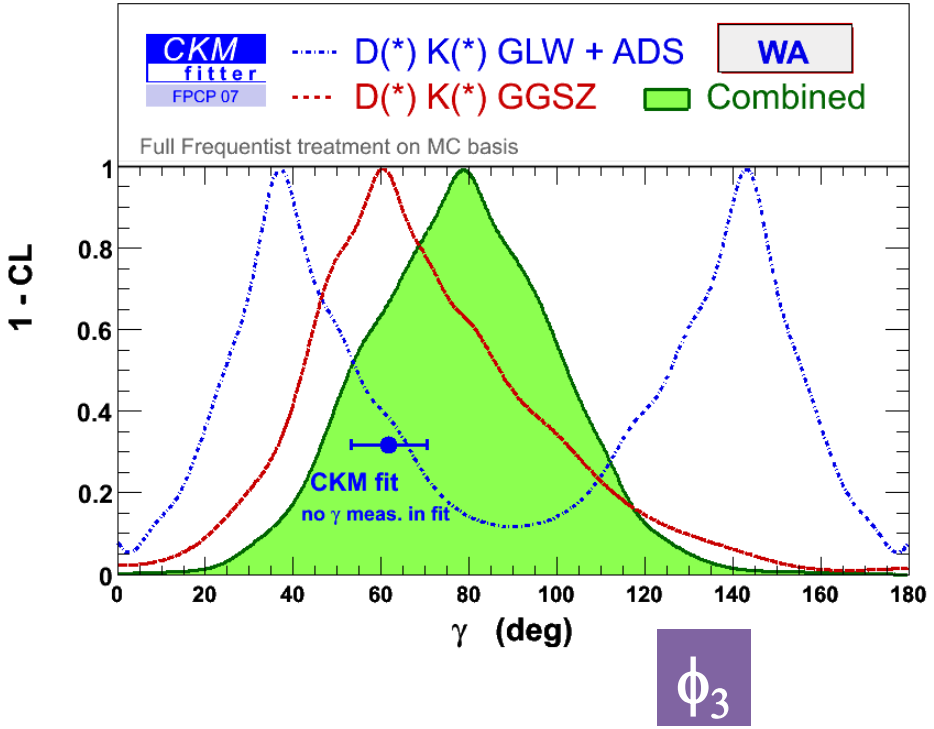
at 68% CL

Results

CKM fit



ϕ_2

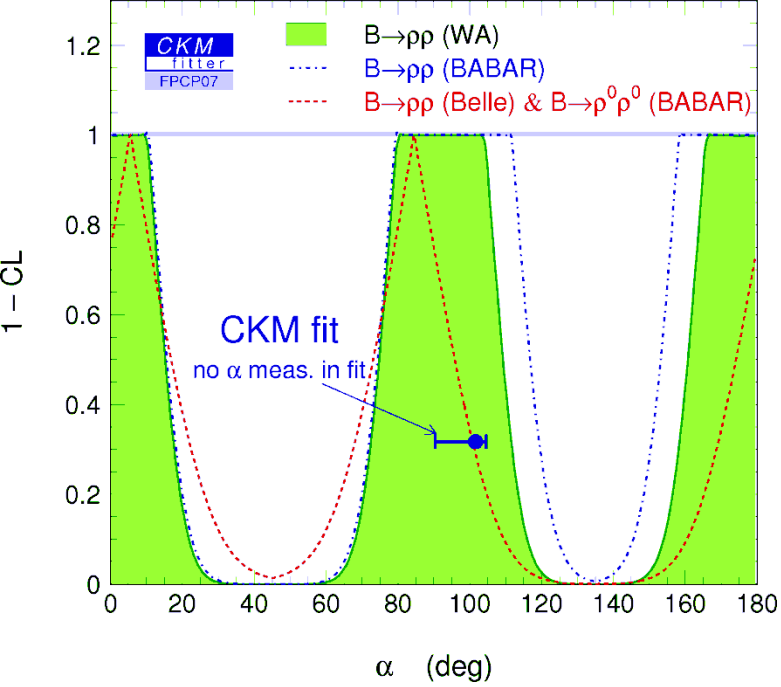


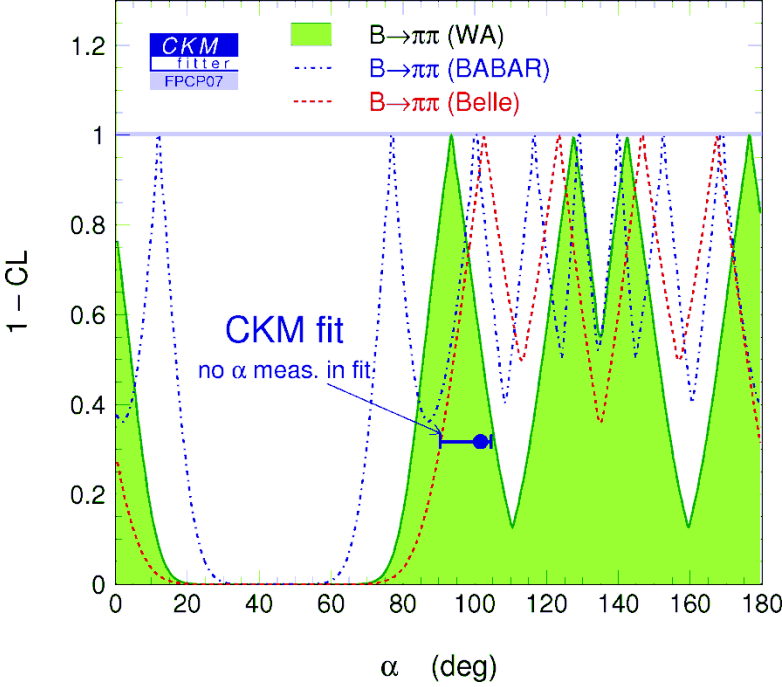
ϕ_3

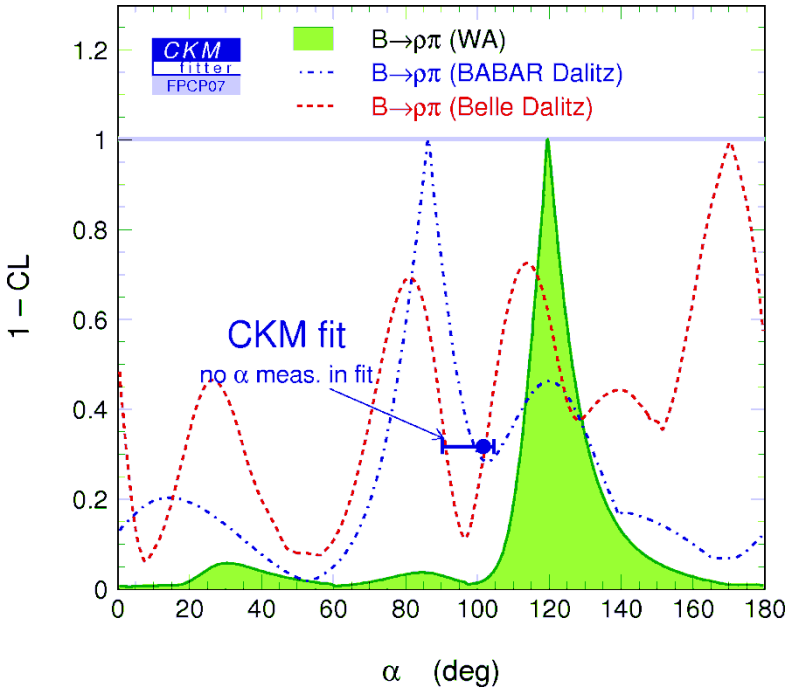
Summary

- ϕ_2 (α) measurement
  - $B \to \pi\pi$ (97 ± 11) °
  - B→ρρ (61 - 107) °
  - B→ρπ (68 - 95) °
  - B→$a_1\pi$ $B.R.(B^0 \to a_1^{\pm}\pi^{\mp})B.R.(a_1 \to \pi^{\pm}\pi^{\pm}\pi^{\mp}) = (14.9 \pm 1.6 \pm 2.3) \times 10^{-6}$
- ϕ_3 (γ) measurement
  - GLW method: weak constraint on ϕ_3
  - ADS methods: r_B<0.18 (90%CL)
  - Dalitz : $\phi_3 = (53^{+15}_{-18} \pm 3 \pm 9)^{\circ}, r_B = 0.16^{+0.05}_{-0.05}(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.05(\text{model})$
  - tCPV: constraint on $|\sin(2\phi_1+\phi_3)|$

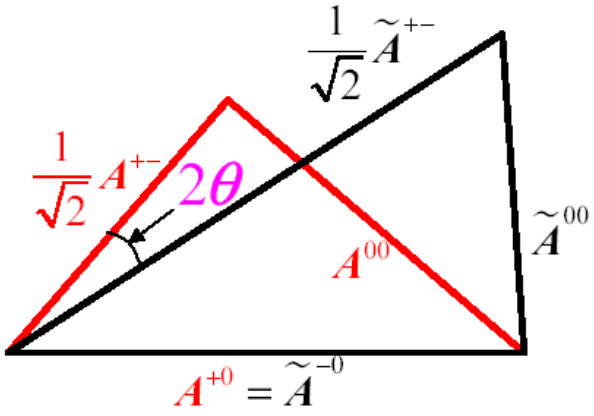
Backups


CKM fitter
FPCP07
B→ρρ (WA)
B→ρρ (BABAR)
B→ρρ (Belle) & B→ρ⁰ρ⁰ (BABAR)
CKM fit
no α meas. in fit
1 – CL
α (deg)


CKM fitter
FPCP07
B→ππ (WA)
B→ππ (BABAR)
B→ππ (Belle)
CKM fit
no α meas. in fit
1 – CL
α (deg)


CKM fitter
FPCP07
B→ρπ (WA)
B→ρπ (BABAR Dalitz)
B→ρπ (Belle Dalitz)
CKM fit
no α meas. in fit
1 – CL
α (deg)

isospin analysis

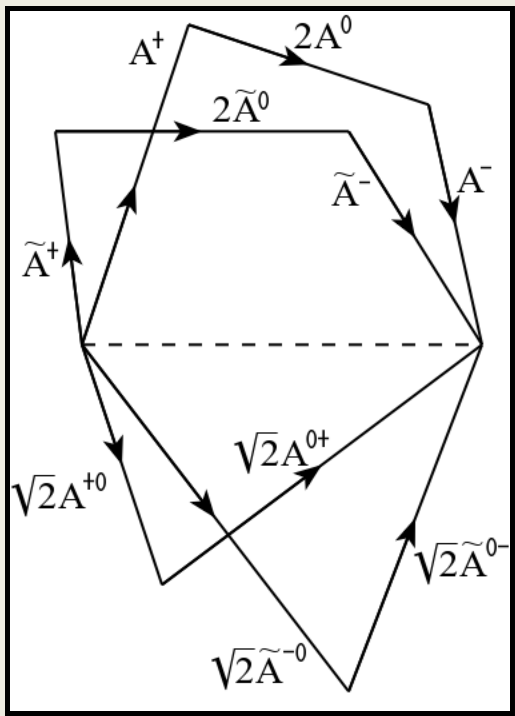


	Amplitude for
$A^{+-}(\bar{A}^{+-})$	$B^0(\bar{B}^0) \to \pi^+\pi^-$
$A^{00}(\bar{A}^{00})$	$B^0(\bar{B}^0) \to \pi^0\pi^0$
$A^{+0}(\bar{A}^{-0})$	$B^+(B^-) \to \pi^+\pi^0(\pi^-\pi^0)$

$\tilde{A}^{ij} = e^{2\phi_3}\bar{A}^{ij}$ 27

Triangle analysis
B → ππ, ρρ

Pentagon analysis
B → ρπ



$e^{+2i\phi_2} =$