Present context of B physics and three body B decays

Particle physics in one page

B physics : CPC and CPV constraints on the Unitarity Triangle

Examples of three body decays

- α from $B^0 \to \pi^+\pi^-\pi^0$
- γ from $B^\pm \to (K_S\pi^+\pi^-)_D K^\pm$
- β from $B^0(\bar{B}^0) \to (K_S\pi^+\pi^-)_D h^0$

  $B^0(\bar{B}^0) \to K^\pm K^\mp K_S,\ K_S\pi^0\pi^0,\ \ldots$
- Direct CP violation $B^\pm \to \pi^\pm\pi^\mp K^\pm$

Conclusions

Particle Physics in one page

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi$$ *The gauge sector (1)*

$$+ \psi_i\lambda_{ij}\psi_j h + h.c.$$ *The flavor sector (2)*

$$+ |D_\mu h|^2 - V(h)$$ *The EWSB sector (3)*

$$+ \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$ *The ν-mass sector (4)*

(1) best tested, at least to per-mille accuracy

- *(2) + (4) : main developments of last 5 years, different in nature, both highly significant*

- (3) Le secteur très peu exploré

In which context this work is happening

Extraordinary data of
B-factories BaBar and Belle

Present fundamental questions

- Physics (EWSB)
  and cosmology (dark matter)
  strongly indicate that there will be
  New Physics at a scale < 1 TeV

- Origin of the electroweak breaking
  is being studied seriously and will develop with LHC

- Flavor physics and CP Violation
  Either discrepancies with the SM appear
  Or one does not find discrepancies,
  why physics beyond the SM is not flavor sensitive ?

- Ideal place to look for New Physics
  In CP conserving (loop processes like $B \to X_s \gamma$)
  or CP violating processes (asymmetries $B \to \phi K_s$)

CP Violation and Flavor Physics

$$(\bar{u}, \bar{c}, \bar{t})\gamma_\mu(1-\gamma_5)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda \cong \sin\theta_C$

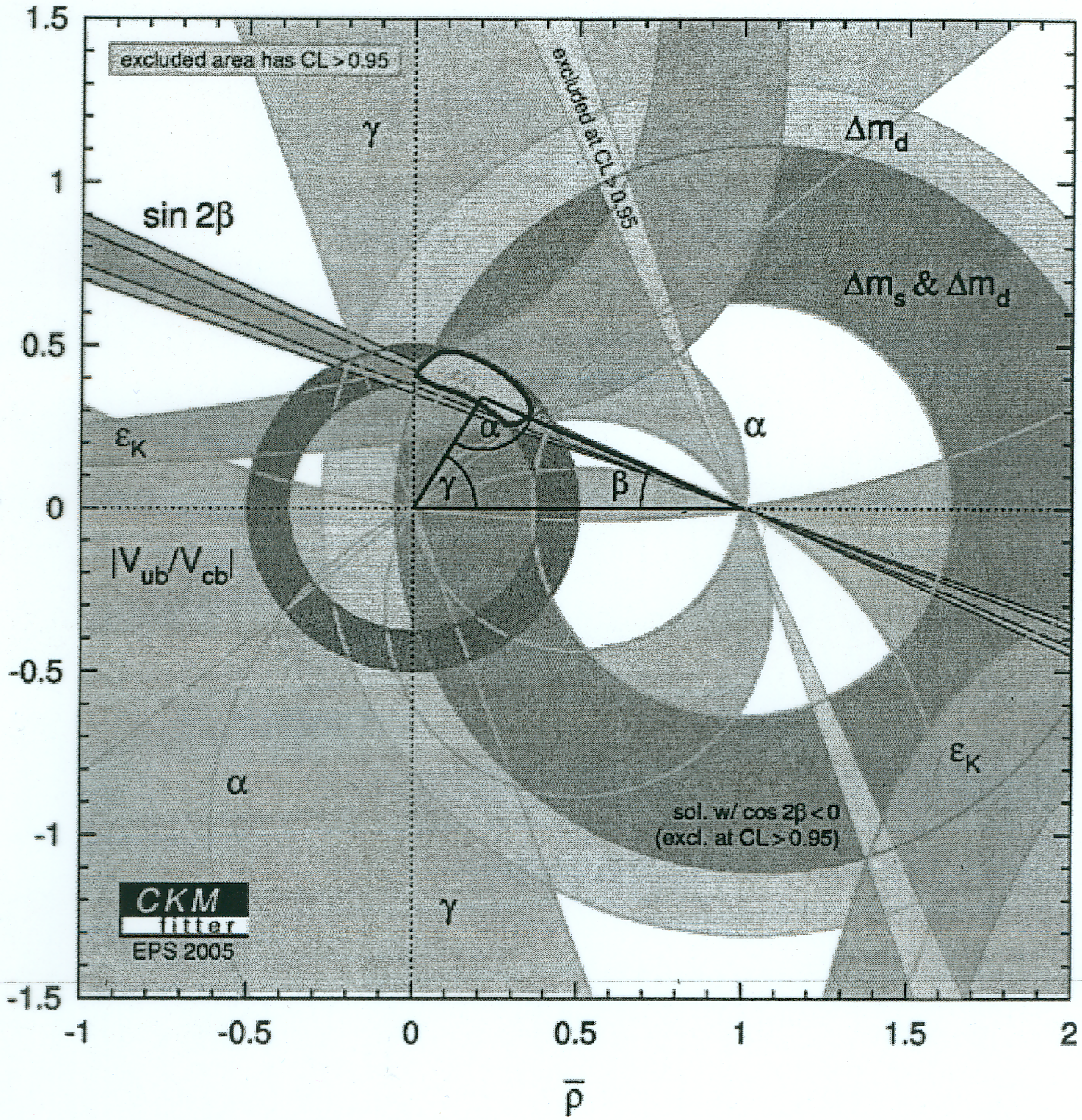
Unitarity triangle B_d^0-$\bar{B}_d^0$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$A\lambda^3(\rho+i\eta) - \lambda\, A\lambda^2 + A\lambda^3(1-\rho-i\eta) = 0$$

- **CP-conserving sector**
  $|V_{cb}|$, $|V_{ub}|$, decays (some very rare)

- **CP-violating sector**
  (angles of the Unitarity Triangle α, β, γ)

Summer 2005



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d
sin 2β
Δm_s & Δm_d
α
ε_K
β
|V_ub/V_cb|
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM
fitter
EPS 2005
η̄
ρ̄

Direct CP violation

Interference between weak phases (Tree-Penguin) and strong phases (absortive or rescattering)

$$A(B \to f) = |A_1|\, e^{i\theta_1} e^{i\delta_1} + |A_2|\, e^{i\theta_2} e^{i\delta_2}$$

$$A(\bar{B} \to \bar{f}) = |A_1|\, e^{-i\theta_1} e^{i\delta_1} + |A_2|\, e^{-i\theta_2} e^{i\delta_2}$$

$$A_{CP} = \frac{2|A_1||A_2|\sin(\delta_1-\delta_2)\sin(\theta_1-\theta_2)}{|A_1|^2+|A_2|^2+2|A_1||A_2|\cos(\delta_1-\delta_2)\cos(\theta_1-\theta_2)}$$

BaBar and Belle (5.7 σ) $A_{K^-\pi^+} = -0.11 \pm 0.02$

Interference between tree $b \to u$ and Penguin $b \to s$

Strong phases are important
cf. QCD Factorization predicts $\delta_{FSI} \sim O(\alpha_s)$

Direct CP violation in three body $B^\pm \to \pi^\pm \pi^\mp K^\pm$

Roughly 3σ effect

BaBar	$A_{CP} = 0.34 \pm 0.13 \pm 0.06 \pm 0.15$
Belle	$A_{CP} = 0.30 \pm 0.11 \pm 0.11$

Interference mixing-decay between $A(B^0 \to f)$ and $A(B^0 \to \bar{B}^0 \to f)$

$$A^f_{CP}(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)}$$

$$= - C_f \cos(\Delta M_B t) + S_f \sin(\Delta M_B t)$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}$$

Example : - B^0_d-$\bar{B}^0_d$ system
- f : CP eigenstate
- Only one CPV phase
(e.g. $b \to c\bar{c}s$, $f = J/\Psi K_S$)

$$\frac{q}{p} = \frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}} = e^{-2i\varphi_{mixing}} = e^{-2i\beta}$$

$$\frac{\bar{A}_f}{A_f} = \eta_f e^{-2i\varphi_{decay}} \qquad \to \qquad |\lambda_f| = 1$$

$$A^{Int}_{CP}(f) = - \eta_f \sin[2(\varphi_{mixing} + \varphi_{decay})] \sin(\Delta M_B t)$$

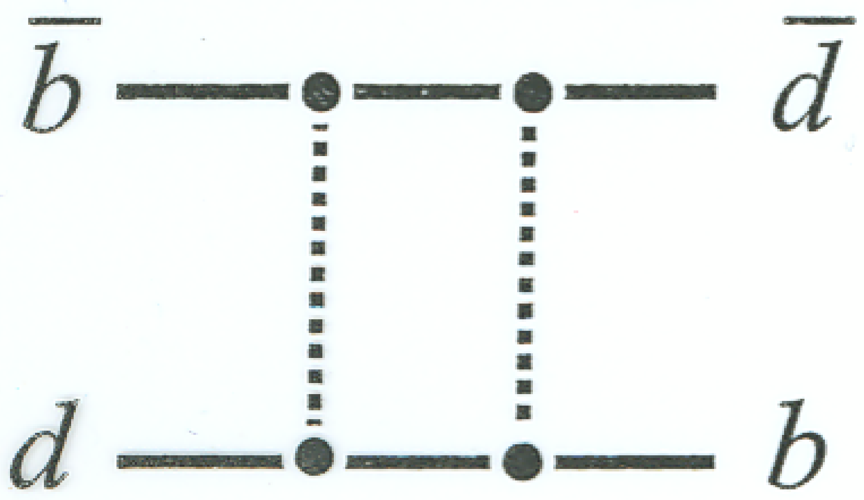
For $J/\Psi K_S$ $\qquad A^{Int}_{CP}(f) = \sin 2\beta \sin(\Delta M_B t)$

Méthodes pour mesurer α

$B \rightarrow \pi\pi,\ \rho\pi,\ \rho\rho$

Interference of suppressed
$b \rightarrow u$ "tree" decay with mixing

B^0 mixing



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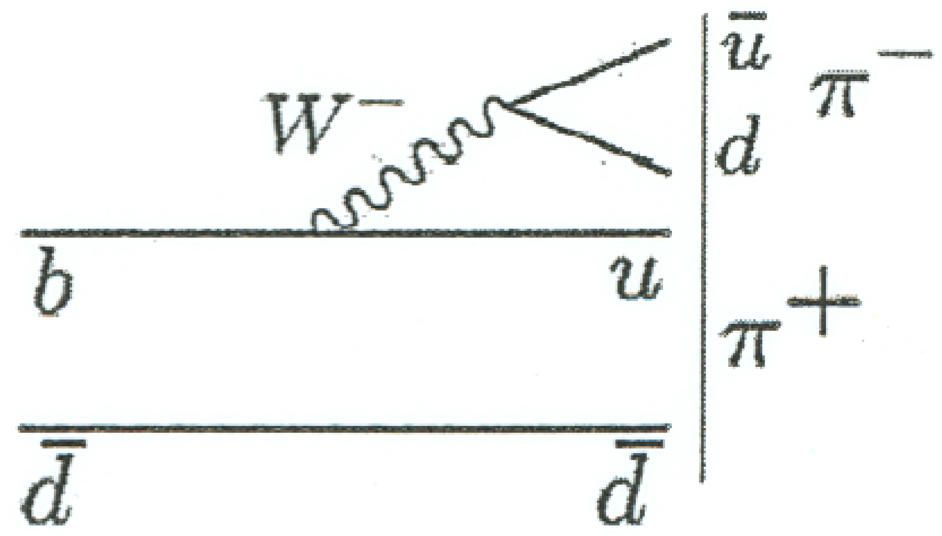
B^0 decay: tree



$q/p \propto V_{tb}^{*}V_{td} / V_{tb}V_{td}^{*}$

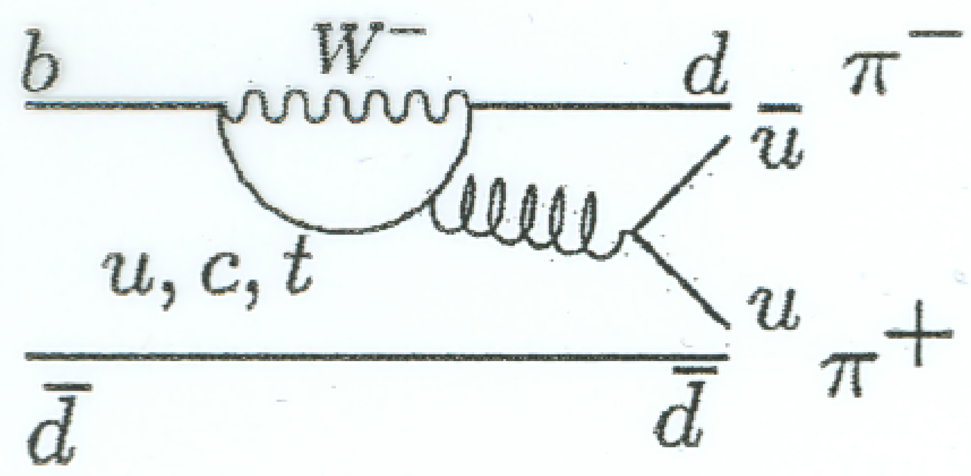
$A \propto V_{ub}^{*}V_{ud}$ $\propto \lambda^3$

$$\lambda_{\pi\pi} = \frac{q}{p}\frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}} = e^{-i2\beta}e^{-i2\gamma} = e^{i2\alpha}$$

but: "penguin"
is sizeable!

⊕

B^0 decay: penguin



$A \propto V_{td}^{*}V_{tb}$ $\propto \lambda^3$

$$\lambda_{\pi\pi} = e^{i2\alpha}\frac{T + Pe^{+i\gamma}e^{i\delta}}{T + Pe^{-i\gamma}e^{i\delta}}$$

With no penguins

$$S_{\pi\pi} = \sin 2\alpha \qquad C_{\pi\pi} = 0$$

With large penguins
and $|P/T| \sim 0.3$

$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2}\,\sin 2\alpha_{eff} \qquad C_{\pi\pi} \propto \sin\delta$$

B → ππ

$B \to \pi^+\pi^-$	$-\eta_{CP}\, S_f$	C_f
BABAR	0.30 ± 0.17	-0.09 ± 0.15
BELLE	1.00 ± 0.22	-0.58 ± 0.17
average	$0.56 \pm 0.13(0.34)$	$-0.31 \pm 0.11(0.24)$

First measurements of tagged $B \to \pi^0\pi^0$ rates, hardest input to isospin analysis: [Gronau, London]

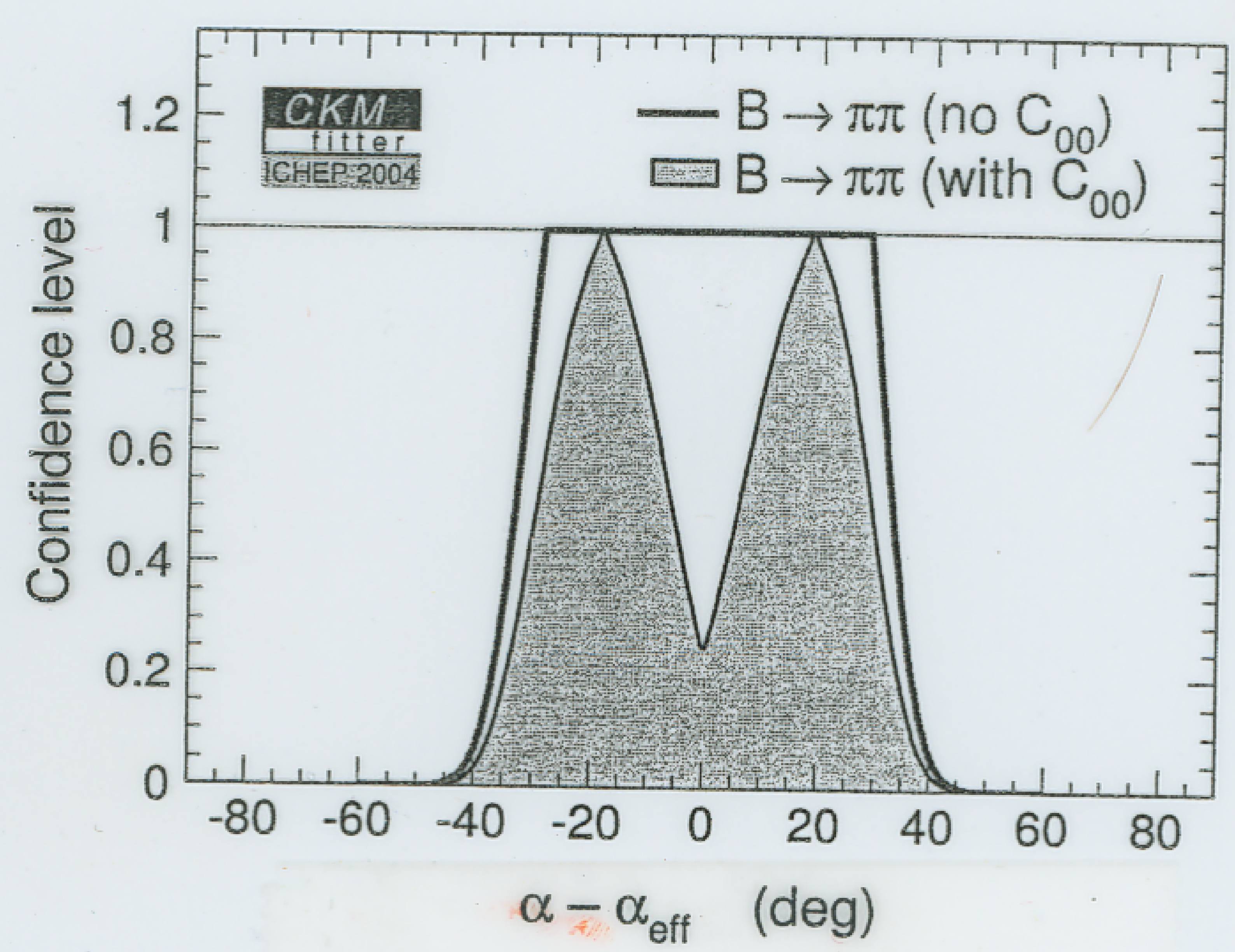
$$\frac{\Gamma(\overline{B} \to \pi^0\pi^0) - \Gamma(B \to \pi^0\pi^0)}{\Gamma(\overline{B} \to \pi^0\pi^0) + \Gamma(B \to \pi^0\pi^0)} = 0.28 \pm 0.39$$

[BABAR, BELLE]

$$\mathcal{B}(B \to \pi^0\pi^0) = (1.51 \pm 0.28) \times 10^{-6}$$

Need a lot more data to pin down $\alpha - \alpha_{\text{eff}}$ from isospin analysis... Bound now:

$$\alpha - \alpha_{\text{eff}} < 39^\circ \ (90\% \ \text{CL})$$



B → ρπ (Dalitz plot)

New: Dalitz plot analysis of the interference regions in $B \to \pi^+\pi^-\pi^0$ [Snyder, Quinn]

$$\alpha = (113^{+27}_{-17} \pm 6)^\circ$$

B→ρρ meilleure détermination de α

ρρ : CP = + domine (polarisation longitudinale)

BaBar $\quad B(B \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ (90% CL)

Pollution du Pingouin petite

$$\frac{B(B\to\pi^0\pi^0)}{B(B\to\pi^+\pi^-)} = 0.33 \pm 0.07 \qquad \frac{B(B\to\rho^0\rho^0)}{B(B\to\rho^+\rho^-)} < 0.04$$

$S_{\rho^+\rho^-}$ et cette borne $\to$ $\alpha = [96 \pm 10 \pm 4 \pm 11]^\circ$

Summary of constraints on α

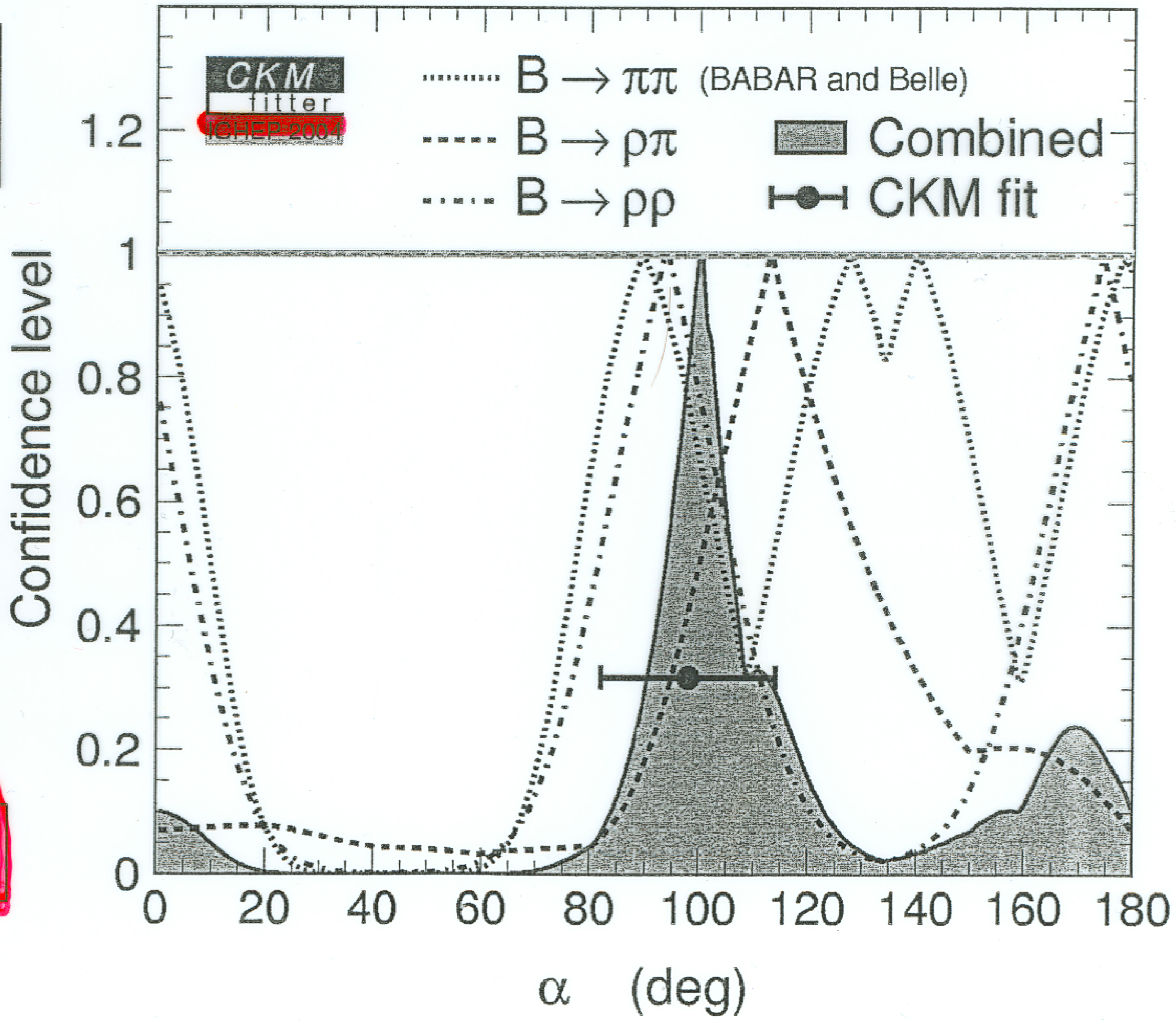
BABAR & Belle combined

Mirror solutions disfavored

From combined $\pi\pi, \rho\pi, \rho\rho$ results:

$$\alpha = \left[100^{+12}_{-11}\right]^\circ$$

CKM indirect constraint fit:
$\alpha = 98 \pm 16^\circ$



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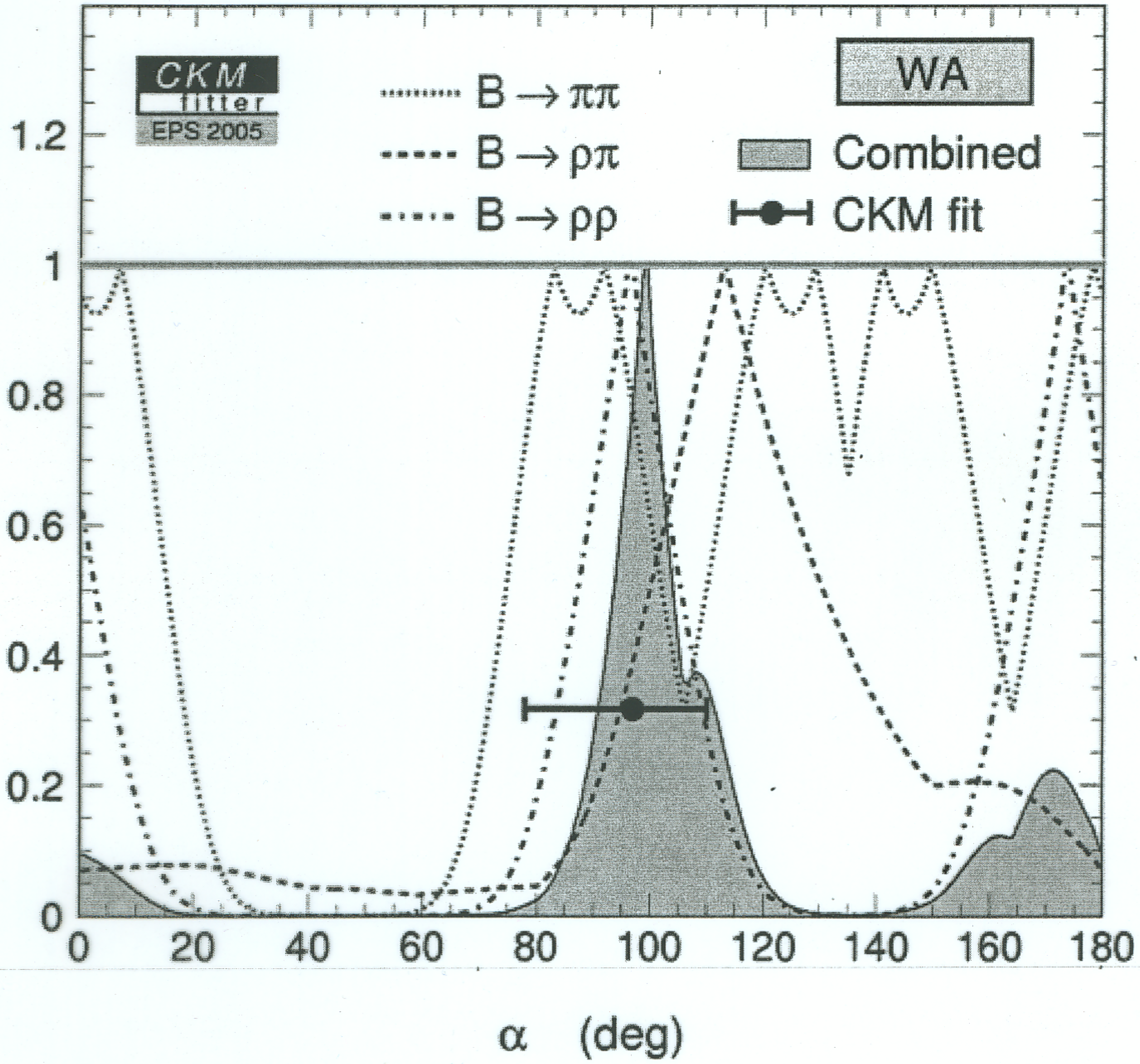


$\alpha = 98.6^{+12.6}_{-8.1}$

cf. talk by Jinwei Wu

Determination of α in $B^0(\bar{B}^0) \to \pi^+\pi^-\pi^0$

Quinn-Snyder method

CP phase (Tree vs. Mixing) $\quad \mathrm{Arg}\left(\frac{V_{ud}V_{ub}^*}{V_{td}V_{tb}^*}\right) = \beta+\gamma = \pi - \alpha$

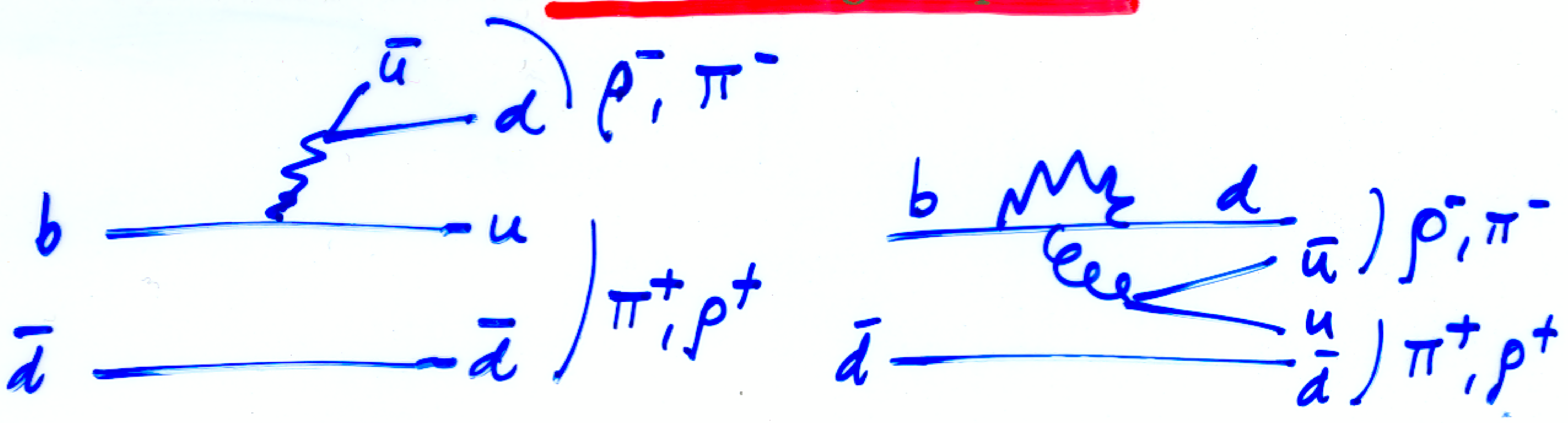
Time-dependent Dalitz plot

$$A(t) = \cos(\Delta Mt/2)\left[f_+A^{+-}+f_-A^{-+}+f_0A^{00}\right]$$
$$\pm\, i\sin(\Delta Mt/2)\left[f_+\bar{A}^{+-}+f_-\bar{A}^{-+}+f_0\bar{A}^{00}\right] \qquad (\pm \text{ from tagging})$$

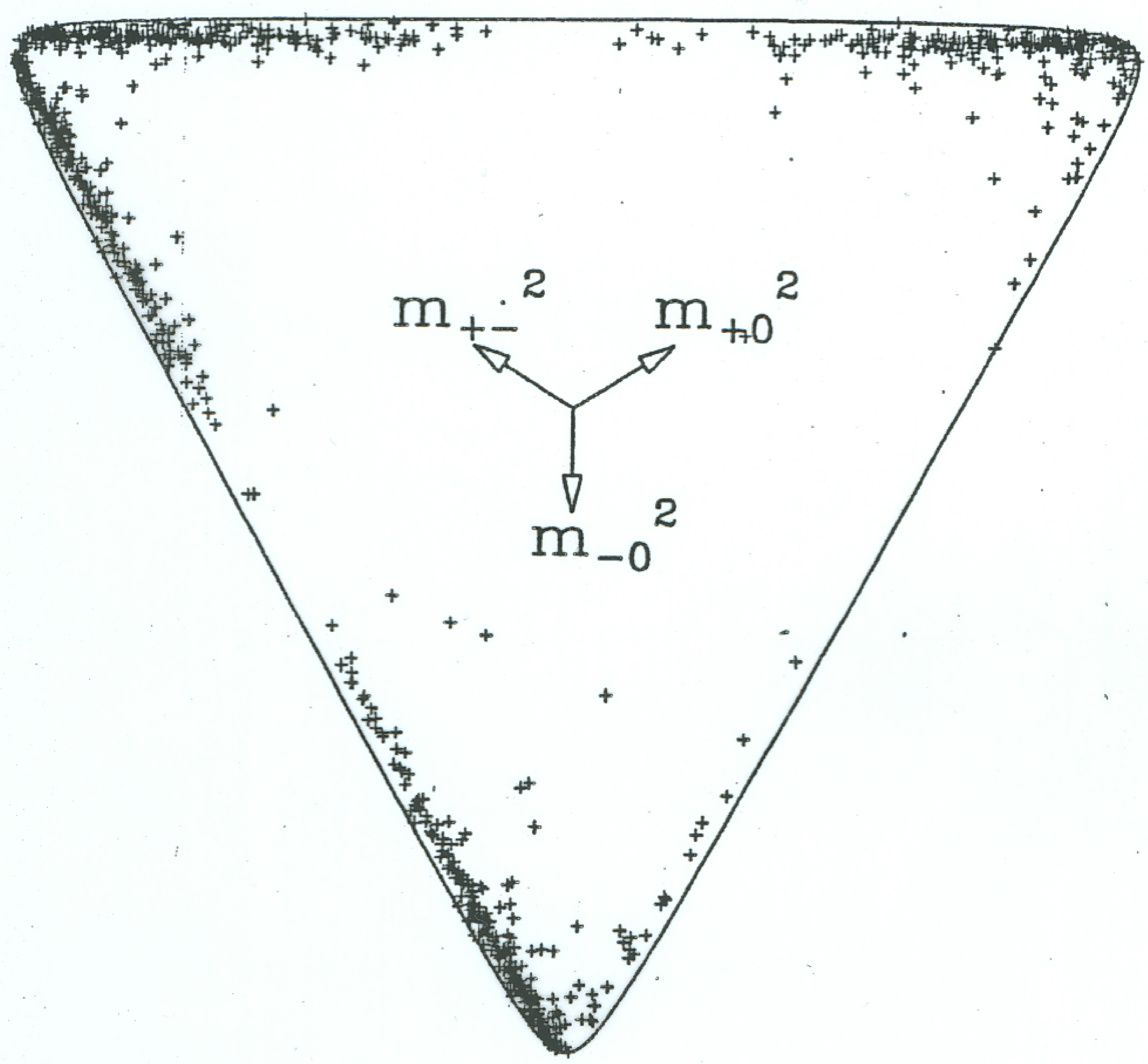
$$f(s) \sim \frac{\cos\theta_H}{s-m_\rho^2+i\Pi(s)} \qquad \Pi(s) = \frac{m_\rho^2}{\sqrt{s}}\left[\frac{p(s)}{p_0}\right]^3\Gamma_\rho(m_\rho^2) \qquad p(s) = \sqrt{\frac{s}{4} - m_\pi^2}$$

$$\frac{p}{q}A(B^0\to\rho^+\pi^-) = A^{+-} = e^{-i\alpha}T^{+-}+P^{+-}$$
$$\frac{p}{q}A(B^0\to\rho^-\pi^+) = A^{-+} = e^{-i\alpha}T^{-+}+P^{-+}$$
$$\frac{p}{q}A(B^0\to\rho^0\pi^0) = A^{00} = e^{-i\alpha}T^{00}+P^{00}$$
$$\frac{q}{p}A(\bar{B}^0\to\rho^+\pi^-) = \bar{A}^{+-} = e^{i\alpha}T^{-+}+P^{+-}$$
$$\frac{q}{p}A(\bar{B}^0\to\rho^-\pi^+) = \bar{A}^{-+} = e^{i\alpha}T^{+-}+P^{+-}$$
$$\frac{q}{p}A(\bar{B}^0\to\rho^0\pi^0) = \bar{A}^{00} = e^{i\alpha}T^{00}+P^{00}$$

The known variation over the Dalitz plot given by Breit-Wigner
→ determination of α and strong FSI phases



BaBar book



A Dalitz plot showing 1200 $B \rightarrow \rho\pi$ events, generated with the Small Penguins set of amplitudes. The $\rho^0\pi^0$ band is noticeably depleted. The events are concentrated at the ends of the ρ bands because of the longitudinal polarization of the ρ

Typical interference terms

Neglecting Penguins

$$\left\{ \begin{array}{l} B^0 \rightarrow \rho^+\pi^- \\ B^0 \rightarrow \rho^-\pi^+ \end{array} \right\} \rightarrow \pi^+\pi^-\pi^0$$ gives δ

No α dependence, but phase dependence from BW and FSI

$$B^0(t) \rightarrow \left\{ \begin{array}{l} B^0 \rightarrow \rho^+\pi^- \\ \bar{B}^0 \rightarrow \rho^-\pi^+ \end{array} \right\} \rightarrow \pi^+\pi^-\pi^0$$ gives 2α

Phase dependence on BW

$$\mathrm{Im}(f_+ f_+^* e^{-2i\alpha}) = \mathrm{Im}(f_+ f_+^*)\cos 2\alpha + \mathrm{Re}(f_+ f_+^*)\sin 2\alpha$$

$$B^0(t) \rightarrow \left\{ \begin{array}{l} B^0 \\ \bar{B}^0 \end{array} \right\} \rightarrow \rho^+\pi^- \rightarrow \pi^+\pi^-\pi^0$$ gives $\sin(2\alpha \pm \delta)$

No phase dependence from BW ($|f|^2$)

dependence $\sin(\Delta M t)\ \mathrm{Im}(TT' e^{\pm 2i\alpha})$

for charged ρ s $T \neq T'$

terms $\sin(2\alpha \pm \delta)$ $\delta = \mathrm{Arg}[T^{-+}(T^{+-})^*]$

for neutral ρ s $T = T'$

dependence $\sin 2\alpha$

Eight degenerate solutions by measuring

$$B^0(t) \to \left\{ \begin{matrix} B^0 \\ \bar{B}^0 \end{matrix} \right\} \to \rho^+\pi^-, \rho^-\pi^+ \qquad \to \qquad \sin(2\alpha \pm \delta)$$

neglecting Penguins and interference between ρ bands

(α', δ')	$\sin 2\alpha'$	$\cos 2\alpha'$
(α, δ)	$\sin 2\alpha$	$\cos 2\alpha$
$(\frac{\pi}{4} - \frac{\delta}{2}, \frac{\pi}{2} - 2\alpha)$	$\cos\delta$	$\sin\delta$
$(\frac{\pi}{2} + \alpha, \pi + \delta)$	$-\sin 2\alpha$	$-\cos 2\alpha$
$(\frac{3\pi}{4} - \frac{\delta}{2}, \frac{3\pi}{2} - 2\alpha)$	$-\cos\delta$	$-\sin\delta$
$(\frac{\pi}{4} + \frac{\delta}{2}, -\frac{\pi}{2} + 2\alpha)$	$\cos\delta$	$-\sin\delta$
$(\frac{\pi}{2} - \alpha, -\delta)$	$\sin 2\alpha$	$-\cos 2\alpha$
$(\frac{3\pi}{4} + \frac{\delta}{2}, -\frac{3\pi}{2} + 2\alpha)$	$-\cos\delta$	$\sin\delta$
$(-\alpha, \pi - \delta)$	$-\sin 2\alpha$	$\cos 2\alpha$

Interference between various intermediate states contributing to the same kinematic 3π region

Dependence on $\cos 2\alpha$ as well as on $\sin 2\alpha$

even with vanishing Penguins some degeneracies are lifted

ambiguity $\alpha \to \frac{\pi}{2} - \alpha$

Analysis in principle fits tree and penguin contributions (10 parameters)

Uncertainties

Assumption of ρ dominance has no theoretical basis

Other resonances can contribute to 3π
$f_0(400)$, $f_0(980)$, $f_2(1270)$, $\rho_3(1690)$, $f_4(2050)$

Nonresonant 3π (flat piece, to be fitted in center of Dalitz plot)

Electroweak Penguins

Analysis of $B^0 \to \rho\pi$ disfavours solution $\alpha + \frac{\pi}{2}$

Combining $B^0 \to \rho\rho$ with $B^0 \to \rho\pi$
(CKMFitter, UTFit, Marie-Hélène Schune 2005)

$$\alpha = 99^{+12^\circ}_{-9}$$

β from three body penguin modes
$B \rightarrow 3K$ by BaBar and Belle

- $B^0(\bar{B}^0) \rightarrow K^{\pm}K^{\mp}K_S$

$S_f = -(f_+ - f_-)\sin 2\beta$ $\qquad$ $C_f = 0$

Corrections

u-quark Penguin

$b \rightarrow u$ tree

Measurements of f_+ and $\sin 2\beta$

$f_+ \sim 0.9$ $\qquad$ $\sin 2\beta \sim 0.55 - 0.60$ $\qquad$ (large errors)

- $B^0(\bar{B}^0) \rightarrow K_S K_S K_S$

$S_f = -\sin 2\beta$ $\qquad$ $C_f = 0$

Correction

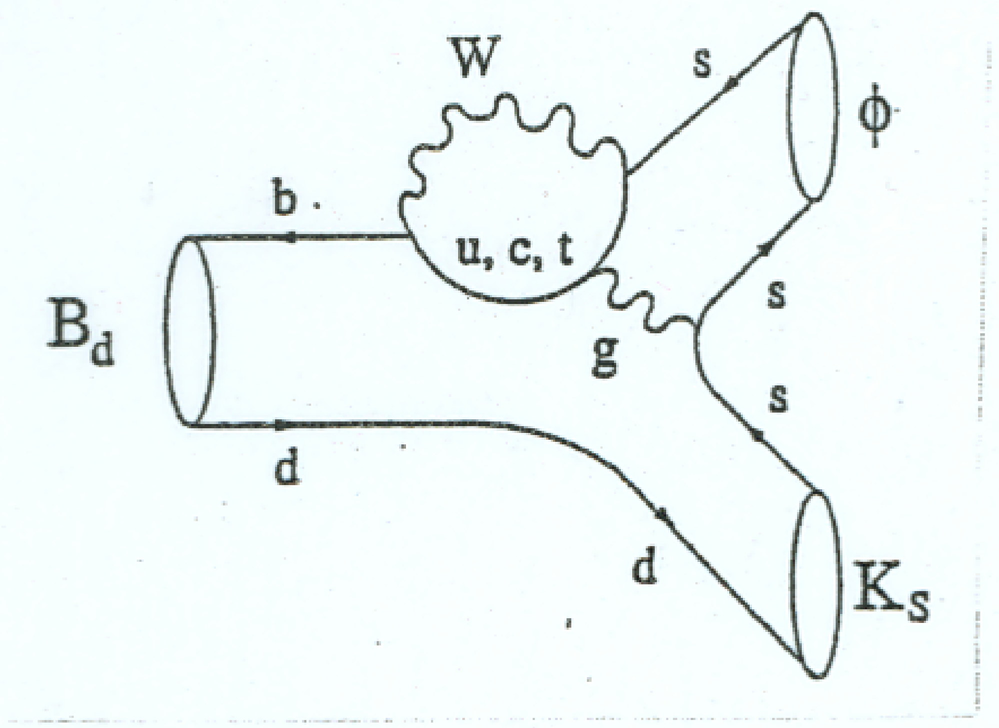
u-quark Penguin

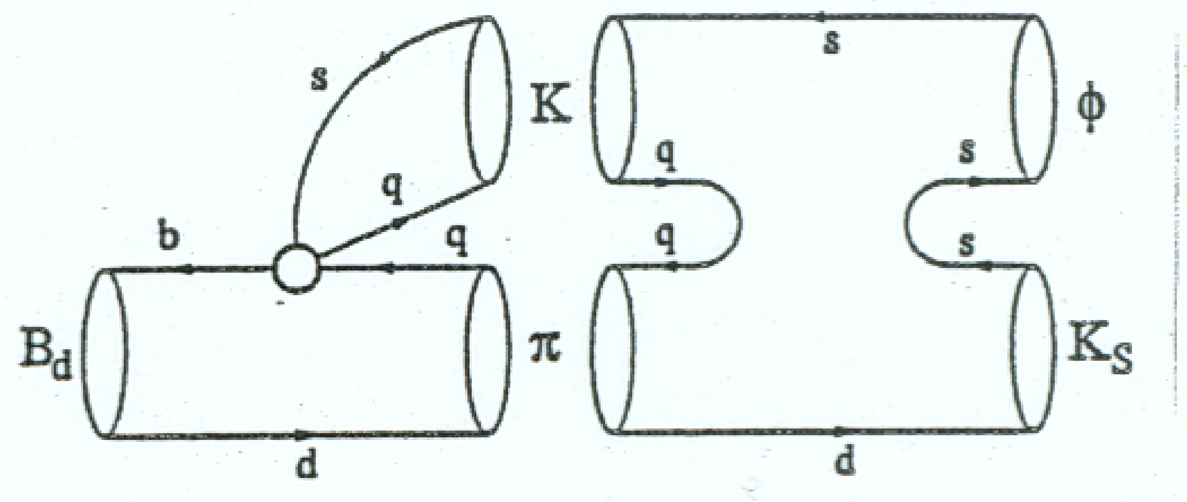
$\sin 2\beta \sim 0.63 - 0.58$

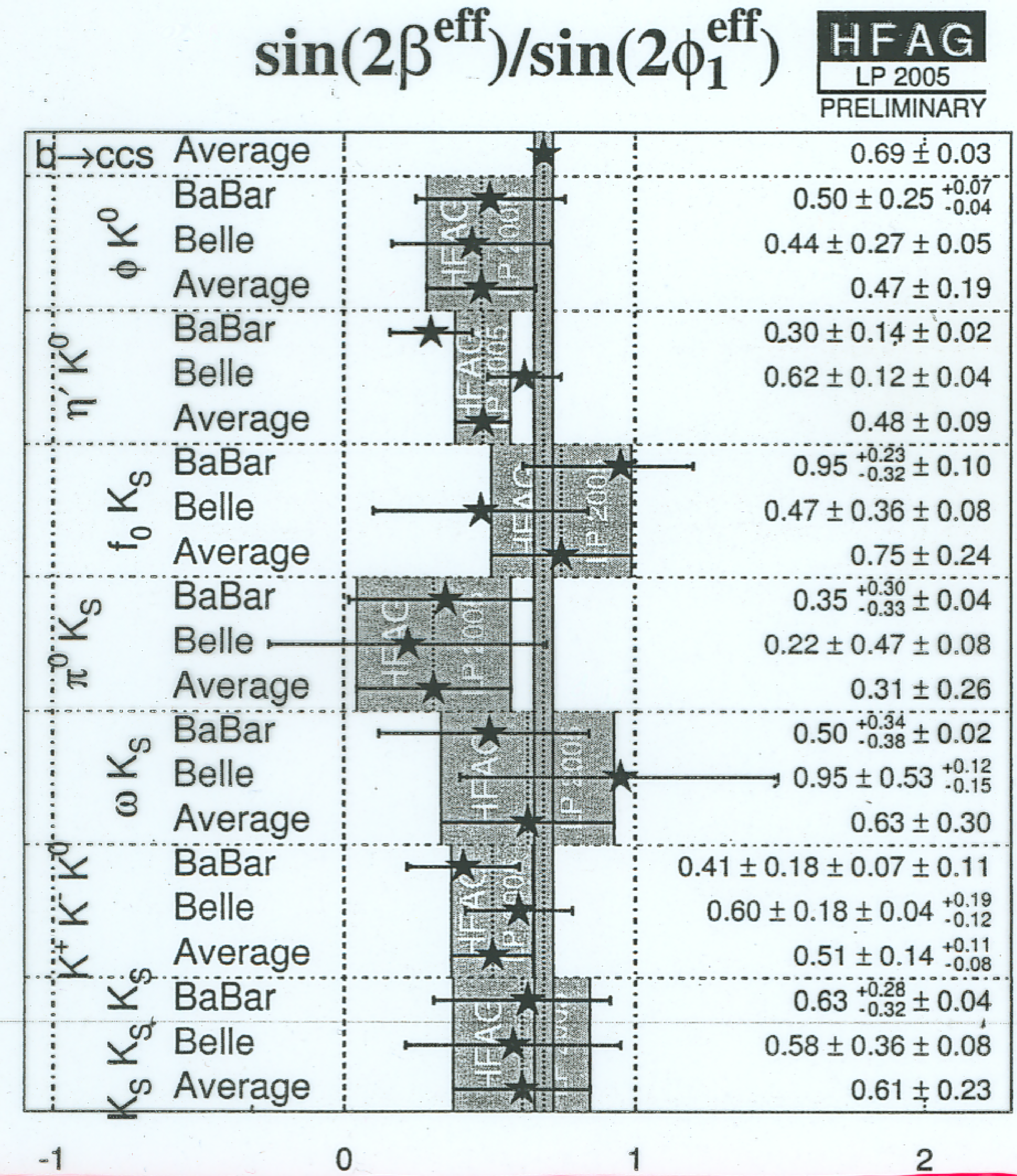
$\sin 2\beta_{eff}$ in transitions $b \to s$

$\bar{A} = V_{cb}V_{cs}^{*}(P_c - P_t + T_c)$
$+ V_{ub}V_{us}^{*}(P_u - P_t + T_u)$

$S_{\varphi K_S} - S_{\Psi K_S}$, $C_{\varphi K_S}$
$\leq O(\lambda^2) = 0.05$







Within 1σ
except $\eta' K^0$

Deviations of $\sin 2\beta_{eff}$ in $b \to s$ penguin decays not settled yet

Determination of γ from Dalitz plot asymmetries $B^{\pm} \to D^{(*)0} K^{(*)\pm}$

$D^0(\bar{D}^0) \to K_S \pi^+ \pi^-$ common final state

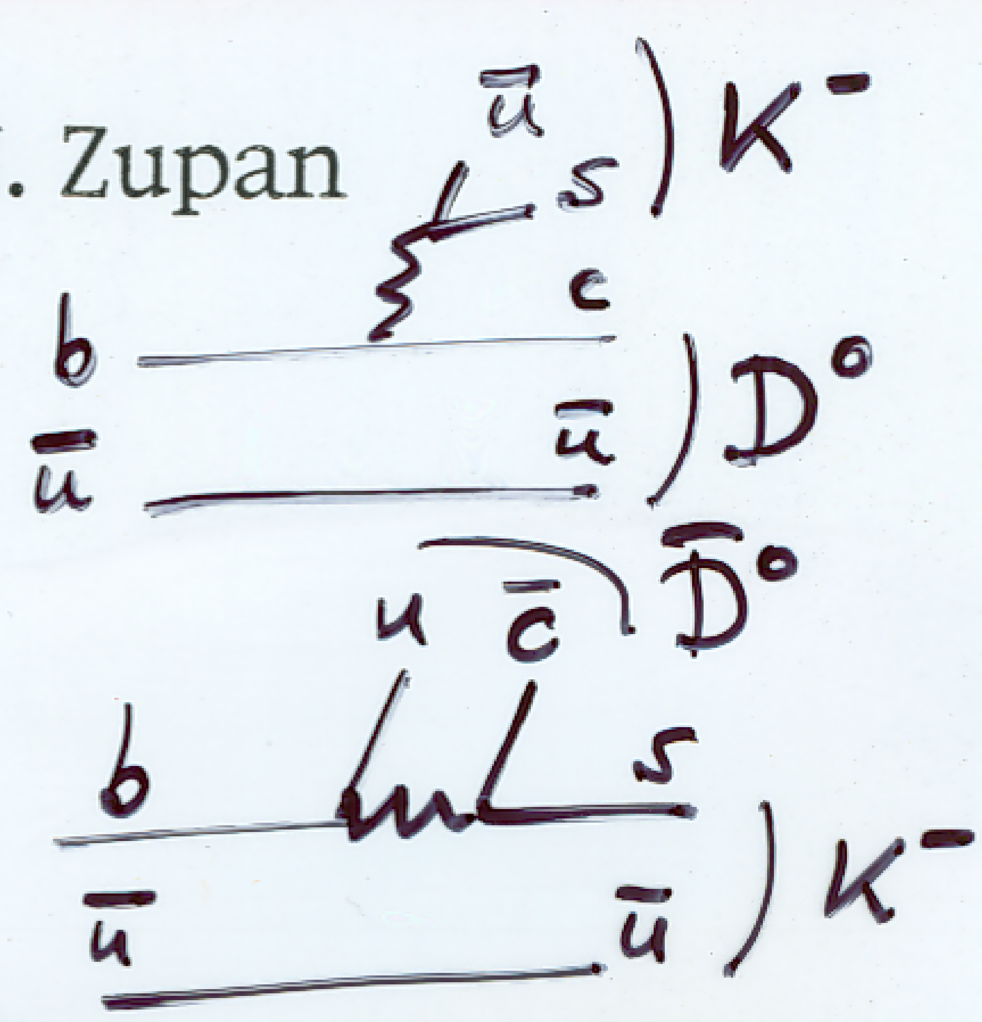
A. Giri, Y. Grossman, A. Soffer and J. Zupan

$A(B^- \to D^0 K^-) \sim V_{cb} V^*_{us}$

$A(B^- \to \bar{D}^0 K^-) \sim V_{ub} V^*_{cs}$

$A(B^+ \to \bar{D}^0 K^+) \sim V^*_{cb} V_{us}$

$A(B^+ \to D^0 K^-) \sim V^*_{ub} V_{cs}$



coherent state

$B^- \to D^0_- K^- \to K_S \pi^+ \pi^- K^-$

$B^+ \to D^0_+ K^+ \to K_S \pi^+ \pi^- K^+$

$D^0_- = D^0 + r e^{i(-\gamma+\delta)} \bar{D}^0$

$D^0_+ = \bar{D}^0 + r e^{i(\gamma+\delta)} D^0$

$m^2_+ = m^2_{K_S \pi^+}$ $\quad$ $m^2_- = m^2_{K_S \pi^-}$

$M(D^0_- \to K_S \pi^+ \pi^-) = f(m^2_-, m^2_+) + r e^{i(-\gamma+\delta)} f(m^2_+, m^2_-)$

$M(D^0_+ \to K_S \pi^+ \pi^-) = f(m^2_+, m^2_-) + r e^{i(\gamma+\delta)} f(m^2_-, m^2_+)$

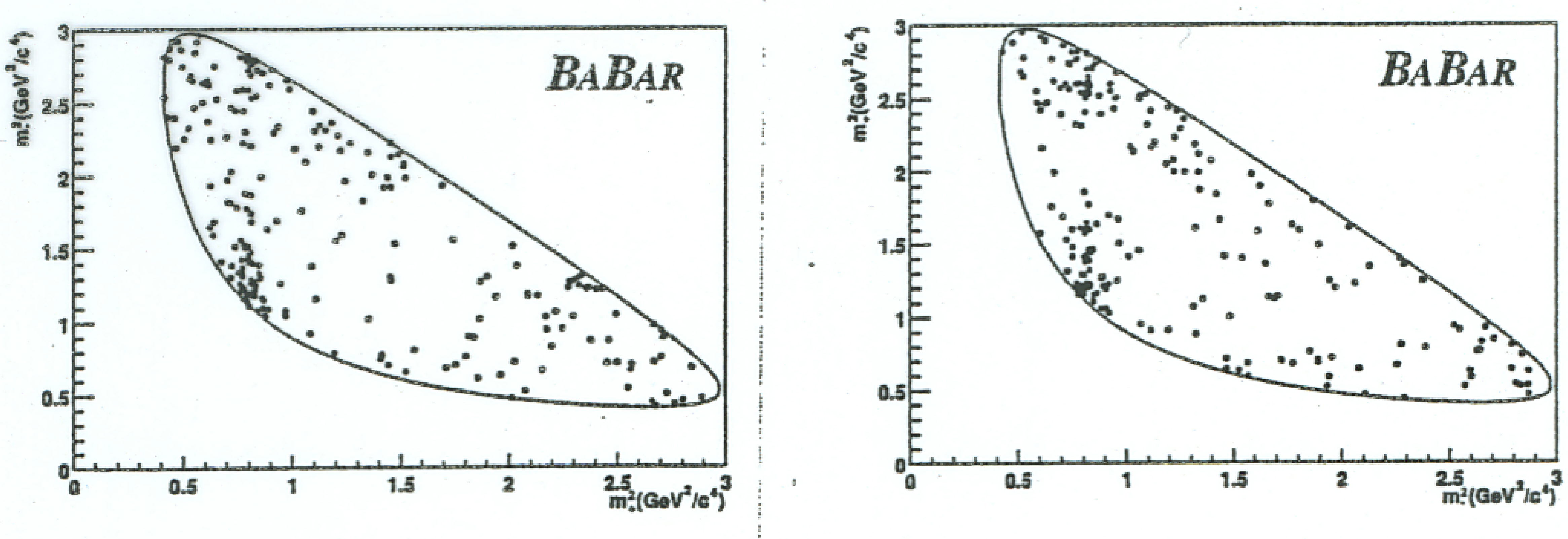
$M(\bar{D}^0 \to K_S \pi^+ \pi^-) = f(m^2_+, m^2_-)$ from continuum $e^+e^- \to q\bar{q}$

Dalitz plots $D^0_- \to K_S \pi^+ \pi^-$ and $D^0_+ \to K_S \pi^+ \pi^-$ are not identical

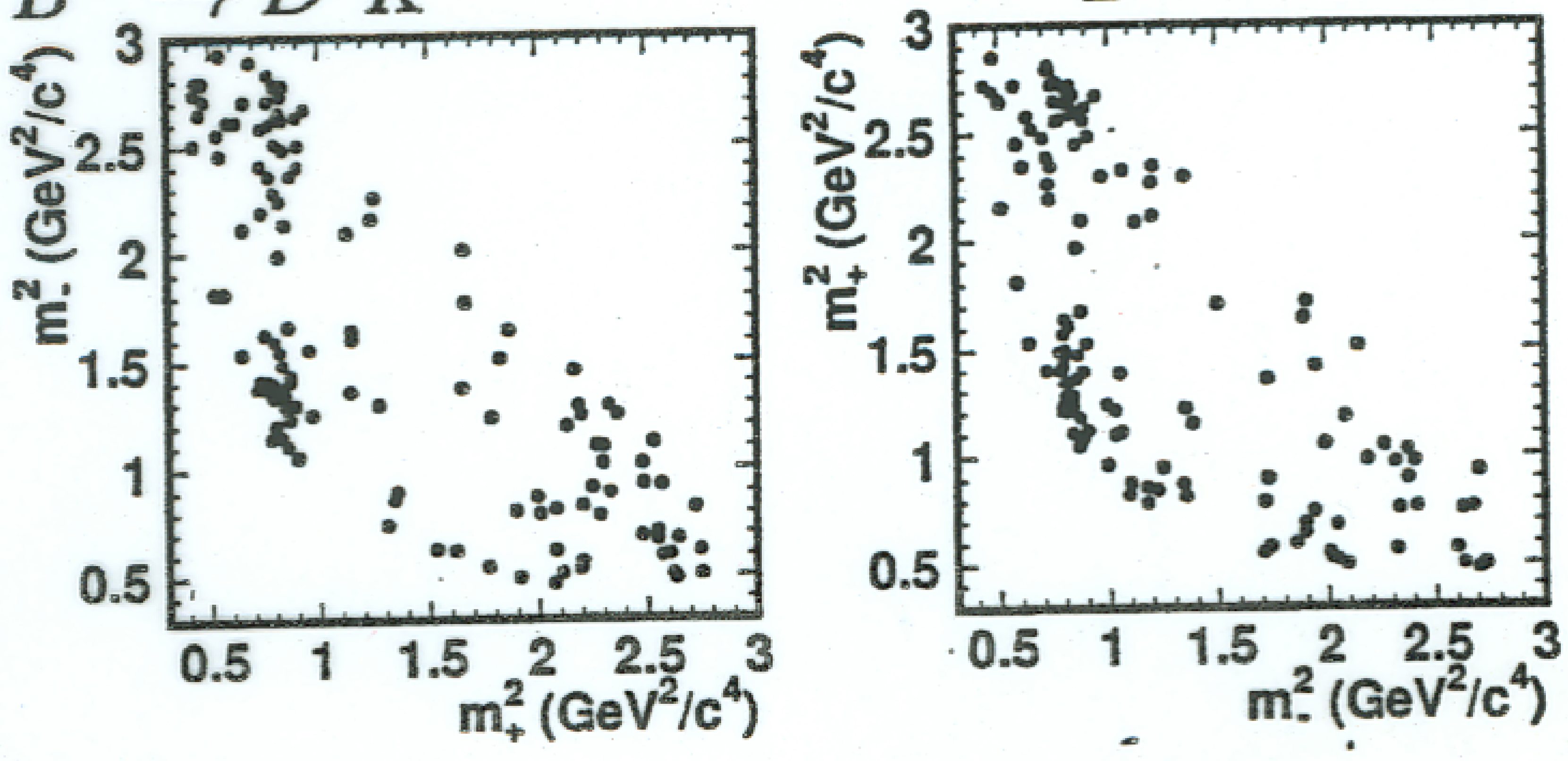
Determination of (r, δ, γ) $\quad$ $r \sim 0.1$ $\quad$ $\gamma = 66 \pm 17°$

Dalitz distributions

$B^+ \to \tilde{D}^0 K^+$ $B^- \to \tilde{D}^0 K^-$

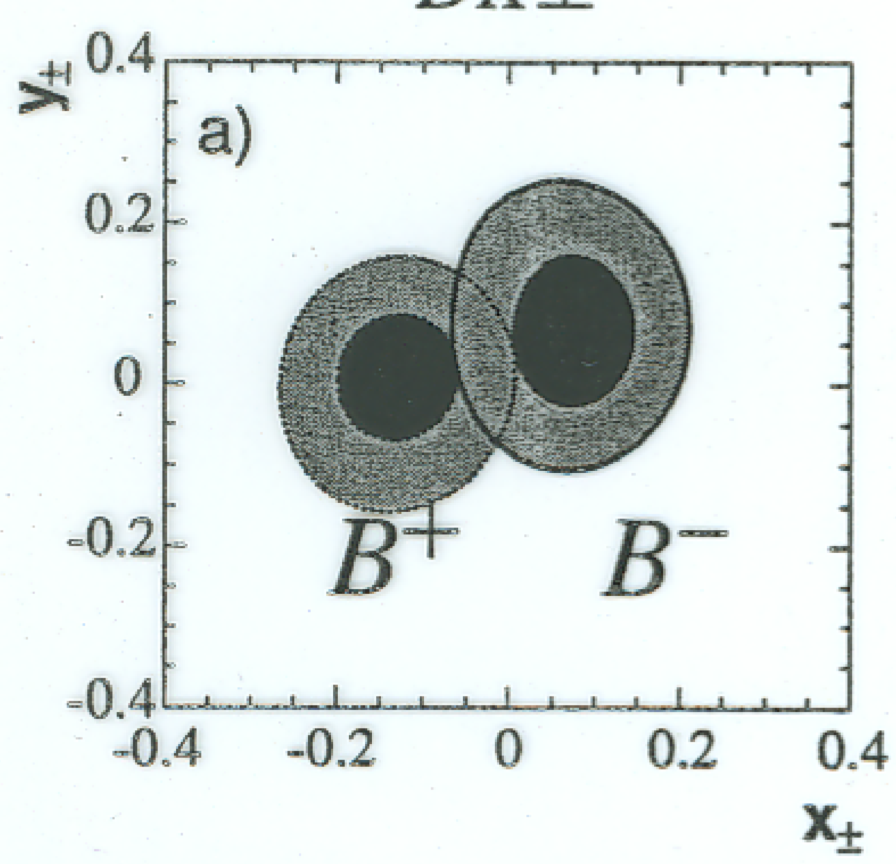


$B^+ \to \tilde{D}^0 K^+$ $B^- \to \tilde{D}^0 K^-$

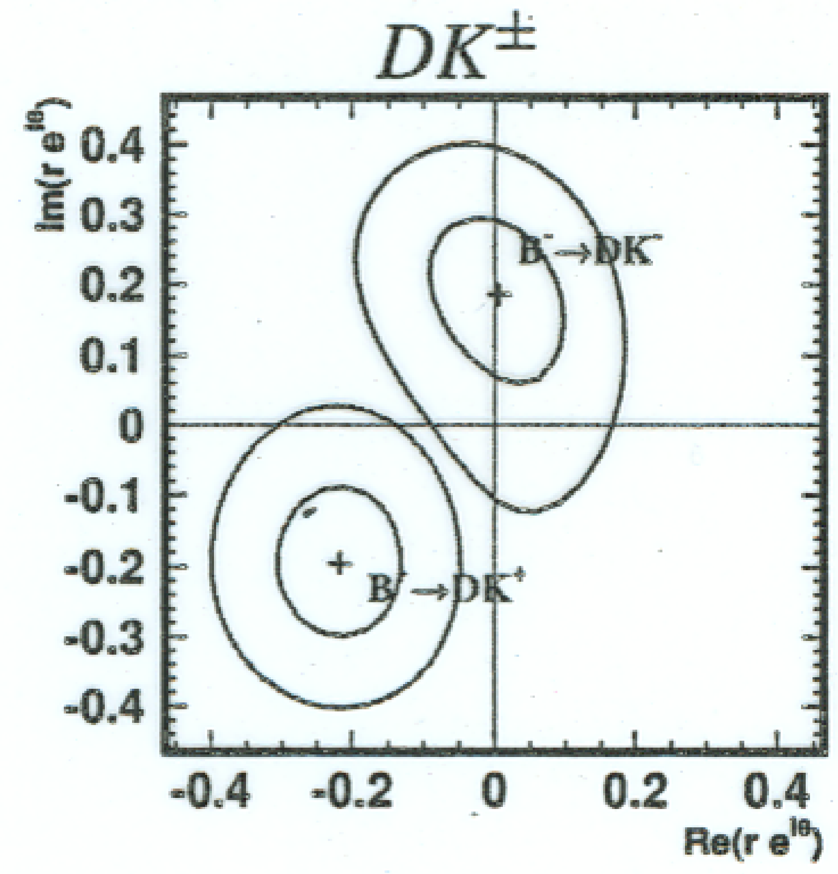


Fitting $Re(r_\pm e^{\pm\gamma+\delta})$ and $Im(r_\pm e^{\pm\gamma+\delta})$

$DK\pm$



$DK^\pm$



Deviation from origin indicates $r \neq 0$

Difference between B^+ and B^- means CPV $\gamma \neq 0$

Measurement of β in $B^0(\bar{B}^0) \to \bar{D}^0(D^0)h^0 \to K_S\pi^+\pi^-h^0$

$D^0(\bar{D}^0) \to K_S\pi^+\pi^-$ can interfere ($\tilde{D}^0$)

$\bar{D}^0(D^0) \to K_S\pi^+\pi^-$ described by $f(m_+^2,m_-^2)$ [$f(m_-^2,m_+^2)$]

Due to β, time-dependent Dalitz plots differ for B^0 and $\bar{B}^0$

$$\left|\cos\left(\frac{\Delta m t}{2}\right)f(m_+^2,m_-^2) - ie^{-2i\beta}\sin\left(\frac{\Delta m t}{2}\right)\eta_{h^0}(-1)^{\ell}f(m_-^2,m_+^2)\right|^2$$

$$\left|\cos\left(\frac{\Delta m t}{2}\right)f(m_-^2,m_+^2) - ie^{2i\beta}\sin\left(\frac{\Delta m t}{2}\right)\eta_{h^0}(-1)^{\ell}f(m_+^2,m_-^2)\right|^2$$

$f(m_+^2,m_-^2)$ from $\bar{D}^0 \to K_S\pi^+\pi^-$ in $e^+e^- \to q\bar{q}$ continuum (model with resonances)

Belle : 300 events ($D\pi^0$, $D\omega$, $D\eta$, $D^*\pi^0$, $D^*\eta$)

$-30° < \beta < 62°$ excludes $\beta = 67°$ at 95% CL

Lifts the $\beta \to \frac{\pi}{2} - \beta$ ambiguity

Résumé of information from Dalitz analysis

- First useful measurement of γ
- Useful measurement of α in $B^0 \to \rho\pi$ disfavouring mirror solutions combined with $\sin 2\alpha$ from $B^0 \to \rho^0\rho^0$
- Resolution of ambiguity $\beta \to \frac{\pi}{2} - \beta$
- Direct CP violation in three body charmless decays $B^\pm \to \pi^\pm\pi^\mp K^\pm$
- CP in three body Penguin $b \to s$ decays $B^0(\bar{B}^0) \to K^\pm K^\mp K_S$

Conclusions

"Dalitz analysis :
a new paradigm for measurements of fundamental parameters"

K. Abe
Lepton-Photon Conference 2005

Fundamental question that will be raised very soon in Flavor Physics and CP Violation

New Physics is expected at energies < 1 TeV, possibly associated with the Higgs

In Flavor Physics, either

- One finds deviations from the Standard Model
- One does not find deviations

Why the New Physics is not flavor-sensitive ?