CP violation and related issues

Part 7: angle ϕ_2 (α)

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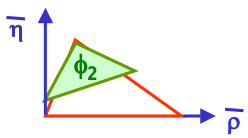


CP asymmetry

CP asymmetry:

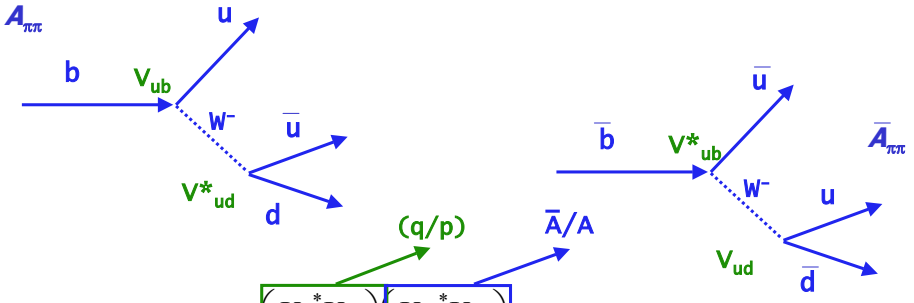
$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)} =$$

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

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

- CP in decay: $|\bar{A}/A| \neq 1$, $|\lambda| \neq 1$
- CP in interference between mixing and decay: $\mathrm{Im}(\lambda) \neq 1$

Decay asymmetry calculation for B->$\pi^+\pi^-$ - tree diagram only

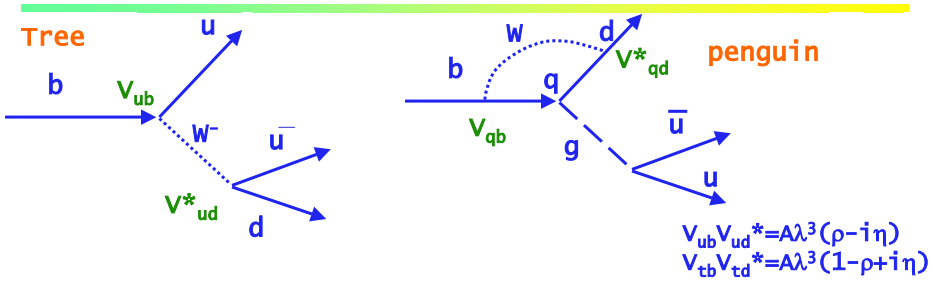


$$\lambda_{\pi\pi} = \eta_{\pi\pi} \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right) \left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*} \right)$$

$$\mathrm{Im}(\lambda_{\pi\pi}) = \sin 2\alpha$$

Neglected possible penguin amplitudes ->

$\pi^+ \pi^-$ - tree vs penguin

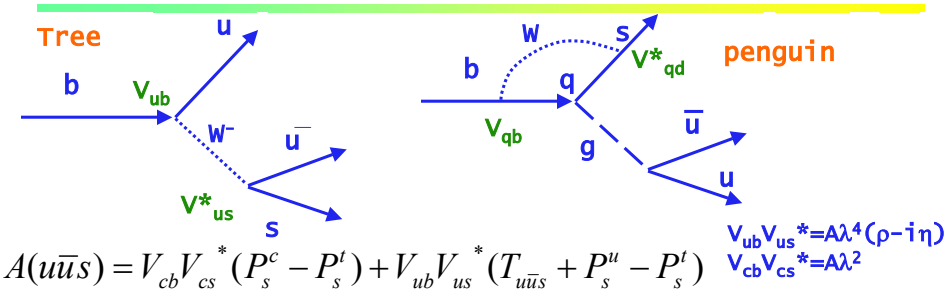


$$A(u\bar{u}d) = V_{tb}V_{td}^{*}(P_d^t - P_d^c) + V_{ub}V_{ud}^{*}(T_{u\bar{u}d} + P_d^u - P_d^t)$$

How much does the penguin contribute?

Compare $B \to K^+\pi^-$ and $B \to \pi^+\pi^-$ →

$\pi^+ K^-$ - tree vs penguin



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

Penguin amplitudes for $B \to K^+\pi^-$ and $B \to \pi^+\pi^-$ are expected to be equal. Contribution to A(uus) in $K^+\pi^-$ enhanced by λ in comparison to $\pi^+\pi^-$

$B \to K^+\pi^-$ tree contribution suppressed by λ^2 vs $\pi^+\pi^-$.

Experiment: $Br(B\to K^+\pi^-) = 1.85\ 10^{-5}$, $Br(B\to\pi^+\pi^-) = 0.48\ 10^{-5}$

→ $Br(B\to\pi^+\pi^-) \sim 1/4\ Br(B\to K^+\pi^-)$ → penguin contribution must be sizeable

Reconstruction of rare B meson decays

$Br(B \to \pi^+\pi^-) = 0.48\ 10^{-5}$
-> Rare decay, have to fight against many background sources.

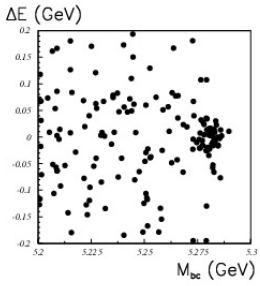
Reconstructing rare B meson decays at Y(4s): use two variables, beam constrained mass M_{bc} and energy diference ΔE

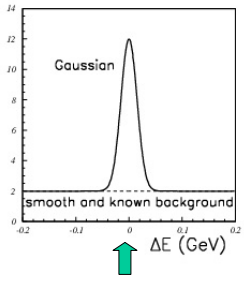
Use event topology parameters to suppress the continuum backgrounds.

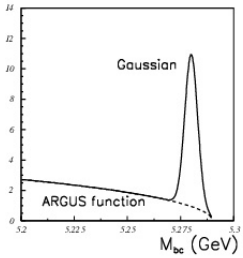
Use particle identification to reduce the background from 4x more copious $B \to K^+\pi^-$ decays.

Exploit the very good momentum resolution to kinematically separate the remaining $B \to K^+\pi^-$ contribution.

Reconstruction of rare B meson decays





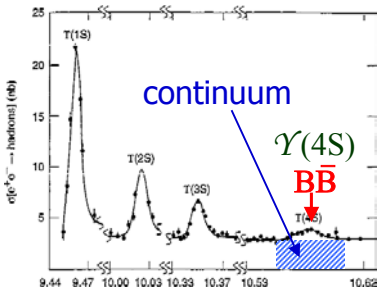


Reconstructing rare B meson decays at Y(4s): use two variables,
beam constrained mass M_{bc}
and
energy diference ΔE

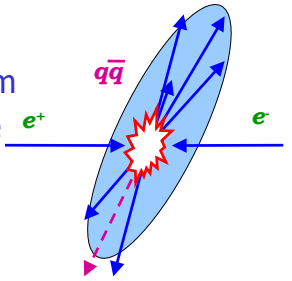
$$\Delta E \equiv \sum E_i - E_{CM}/2$$

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

Continuum suppression



Continuum
Jet-like

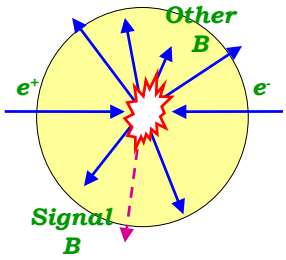


$e^+e^- \rightarrow qq$ "continuum" (~3x BB)

To suppress: use event shape variables

BB

spherical



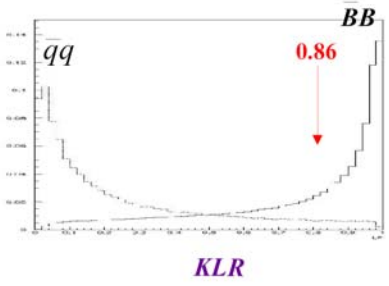
Continuum suppression

$e^+e^- \rightarrow qq$ "continuum" (~3x BB)

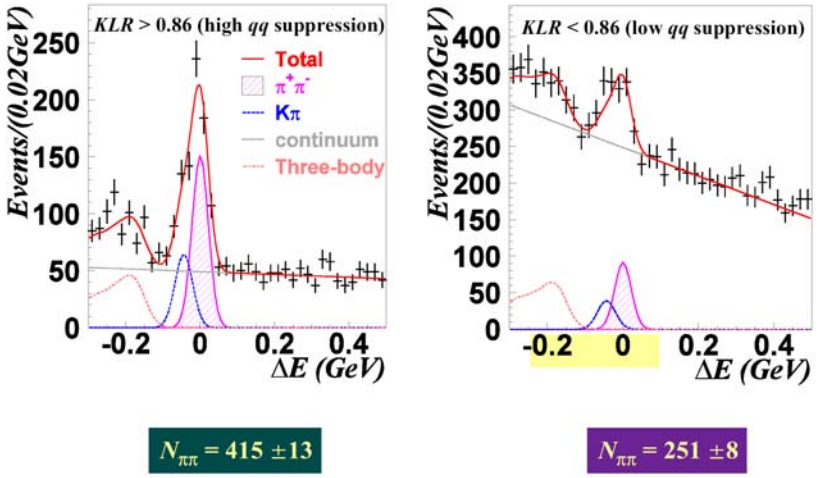
To suppress it use:
- event shape variables
- event axis direction

Combine to a likelihood ratio:

$$KLR \equiv \frac{\mathcal{L}_{B\bar{B}}}{(\mathcal{L}_{B\bar{B}} + \mathcal{L}_{q\bar{q}})}$$



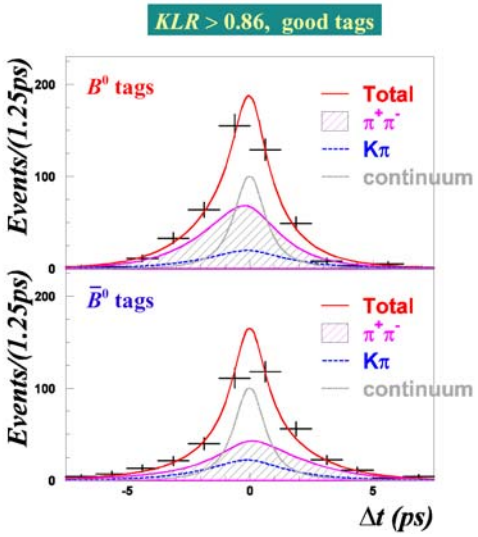
B->$\pi^+ \pi^-$ sample (253/fb) – just published



$N_{\pi\pi} = 415 \pm 13$

$N_{\pi\pi} = 251 \pm 8$

B->$\pi^+ \pi^-$: results of the fit

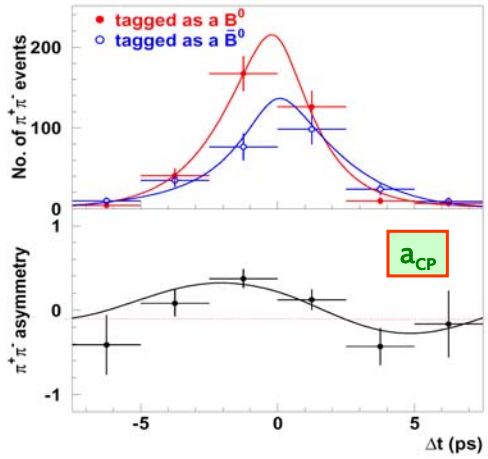


$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$

$\mathcal{A}_{\pi\pi} = 0.56 \pm 0.12 \pm 0.06$

-> direct CP violation!

B->$\pi^+\pi^-$: results of the fit, plotted with background subtracted



$\mathcal{S}_{\pi\pi}$ = -0.67±0.16±0.06

$\mathcal{A}_{\pi\pi}$ = 0.56±0.12±0.06

-> direct CP violation!
Evident on this plot:
Number of anti-B events
< Number of B events

B->$\pi^+\pi^-$: interpretation

Interpretation:

tree level

tree +

$$\lambda_{\pi\pi} = e^{2i\phi_2} \quad \rightarrow \quad \lambda_{\pi\pi} = e^{2i\phi_2}\frac{1+|P/T|e^{\delta+i\phi_3}}{1+|P/T|e^{i\delta-i\phi_3}} \equiv |\lambda_{\pi\pi}|e^{2i\phi_{2eff}}$$

strong phase
diff. P-T
weak phase
(changes sign)

$$A_{\pi\pi} = 0 \quad \rightarrow \quad A_{\pi\pi} \propto \sin\delta$$

$$S_{\pi\pi} = \sin(2\phi_2) \quad \rightarrow \quad S_{\pi\pi} = \sqrt{1-A^2{}_{\pi\pi}}\,\sin(2\phi_{2eff})$$

direct CP

$$A(u\bar{u}d) = V_{cb}V_{cd}^{*}(P_d^c - P_d^t) + V_{ub}V_{ud}^{*}(T_{u\bar{u}d} + P_d^u - P_d^t) =$$
$$= V_{ub}V_{ud}^{*}T_{u\bar{u}d}\left[1 + (P_d^u - P_d^t) + (V_{cb}V_{cd}^{*}/V_{ub}V_{ud}^{*})(P_d^c - P_d^t)\right]$$

$$\gamma \equiv \phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

How to extract ϕ_2, δ and |P/T|?

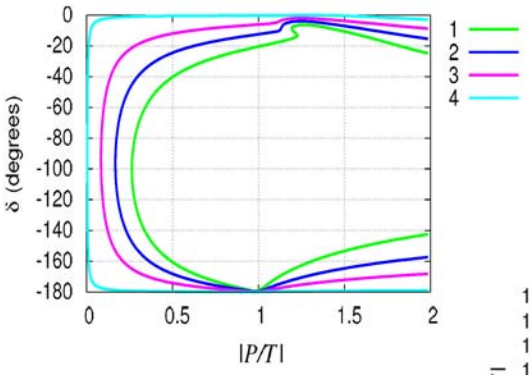
ϕ_{2eff} depends on δ, ϕ_3, ϕ_2 and |P/T|

$\pi = \phi_1 + \phi_2 + \phi_3 \rightarrow \phi_{2eff}$ depends on δ, ϕ_1, ϕ_2 and |P/T|

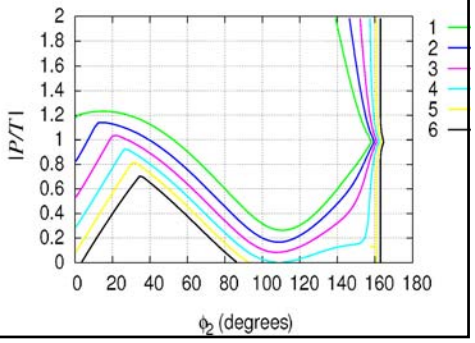
penguin amplitudes $B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$ are equal → limits on |P/T| (~0.3);
considering all interval of δ values one can obtain interval of ϕ_2 values;

isospin relations can be used to constrain δ (or better to say $\phi_2 - \phi_{2eff}$);

Constraints upon ϕ_2, δ and |P/T|



For any |P/T|
$\delta < -4°$ (95% CL)
For any δ
|P/T| > 0.17 (95% CL)

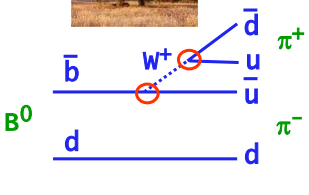


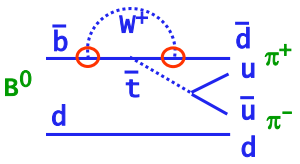
For |P/T|=0.6 (for example)
$72° < \phi_2 < 146°$ (95% CL)

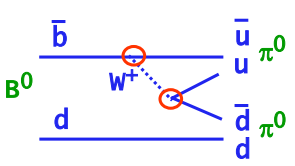
Extracting ϕ_2: isospin relations

$B^0 \to \pi^+\pi^-, \pi^0\pi^0$









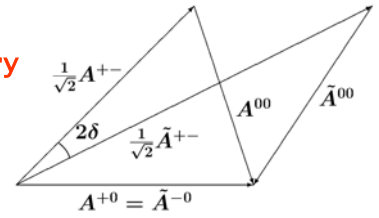
$T \sim V_{ub}^*V_{ud} \sim \lambda^3$ $P \sim V_{tb}^*V_{td} \sim \lambda^3$ $T_c \sim V_{ub}^*V_{ud}$

No pengiun!

Constraint: relation of decay amplitudes in the SU(2) symmetry

$\bar{A}^{+0} = 1/\sqrt{2}\ \bar{A}^{+-} + \bar{A}^{00}$

$A^{-0} = 1/\sqrt{2}\ A^{+-} + A^{00}$

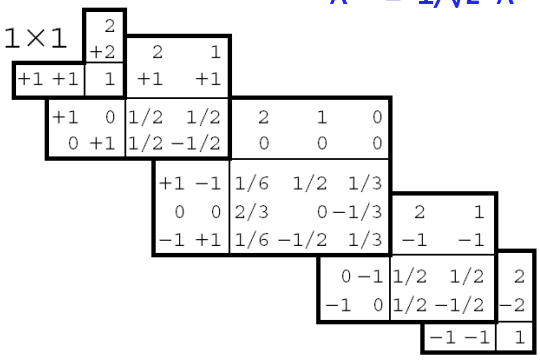


Extracting ϕ_2: isospin relations

How to derive the relation of decay amplitudes within the SU(2) symmetry?

$\bar{A}^{+0} = 1/\sqrt{2}\ \bar{A}^{+-} + \bar{A}^{00}$

$A^{-0} = 1/\sqrt{2}\ A^{+-} + A^{00}$

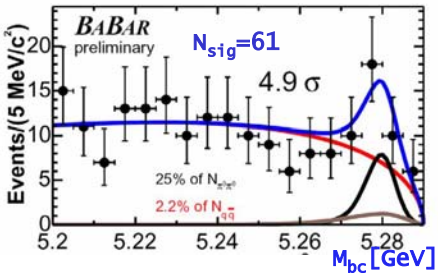


- Symmetrize $\pi\pi$ states
- Decompose in $I_{\pi\pi}$ amplitudes (C.-G. coefficients)
- Rewrite in terms of B->$\pi\pi$ decay amplitudes

$$A(B^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2}A_{3/2,2}$$
$$\frac{1}{\sqrt{2}}A(B^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{12}}A_{3/2,2} - \sqrt{\frac{1}{6}}A_{1/2,0}$$
$$A(B^0 \to \pi^0\pi^0) = \frac{1}{\sqrt{3}}A_{3/2,2} + \sqrt{\frac{1}{6}}A_{1/2,0}$$

$B^0 \to \pi^0\pi^0$

A very difficult channel - finally measured!



227M BB̄, Belle

Br($B^0 \to \pi^0\pi^0$)= $(1.17 \pm 0.32 \pm 0.10)\times10^{-6}$

$\mathcal{A}_{CP}$= $0.12 \pm 0.56 \pm 0.06$

274M BB̄, BaBar N_{sig}=82

Br($B^0 \to \pi^0\pi^0$)= $(2.32 \pm 0.45 \pm 0.20)\times10^{-6}$

$\mathcal{A}_{CP}$= $0.43 \pm 0.51 \pm 0.17$

Extraction of ϕ_2

Use measured BRs and asymmetries in all three $B \to \pi\pi$ decays $\to$ extract ϕ_2

Similar analysis as for $B \to \pi\pi$ also for $B \to \rho\rho$

(ϕ_2^{eff} closer to ϕ_2)

... and for $B \to \rho\pi$

BaBar/Belle

S_{+-} $Br(B^0 \to \pi^0\pi^0)$

A_{+-} $Br(B^0 \to \pi^+\pi^-)$

$\mathcal{A}_{CP}$ $Br(B^+ \to \pi^+\pi^0)$

BaBar

Similar from $B \to \rho\rho$

BaBar/Belle

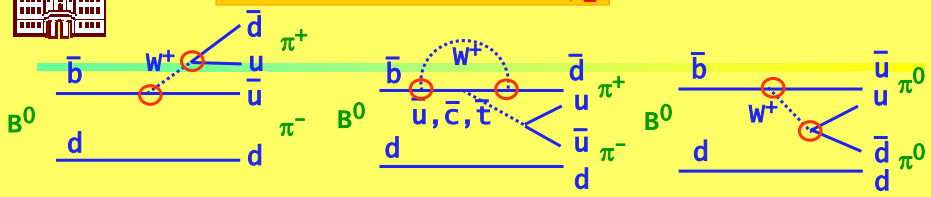
Similar from $B \to \rho\pi$

$\phi_2 = 106^o \pm {}^{8^o}_{11^o}$

Backup slides

CKM Matrix – ϕ_2

backup slide



$T \sim V_{ub}^* V_{ud} \sim \lambda^3$ $\quad P \sim V_{tb}^* V_{td} \sim \lambda^3$ $\quad T_c \sim V_{ub}^* V_{ud}$

$M^{+-} = -Te^{-i\phi_2} + Pe^{i\delta_P}$

$M^{+0} = 1/\sqrt{2}(T_c e^{i\delta_C} + T)e^{-i\phi_2}$

$M^{00} = 1/\sqrt{2}(T_c e^{i\delta_C} e^{-i\phi_2} + Pe^{i\delta_P})$

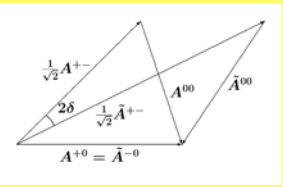
$S = \sqrt{(1-A^2)}\sin 2\phi_2^{eff}$

$A \sim \sin\delta_P$

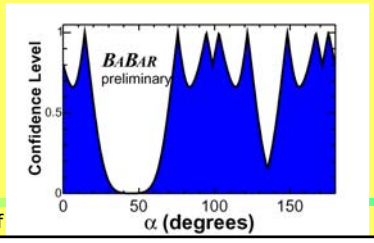
$S = \sin 2\phi_2$

$A = 0$

Isospin relations for $B \to \pi\pi$



ϕ_2 from $B \to \pi\pi$ BaBar



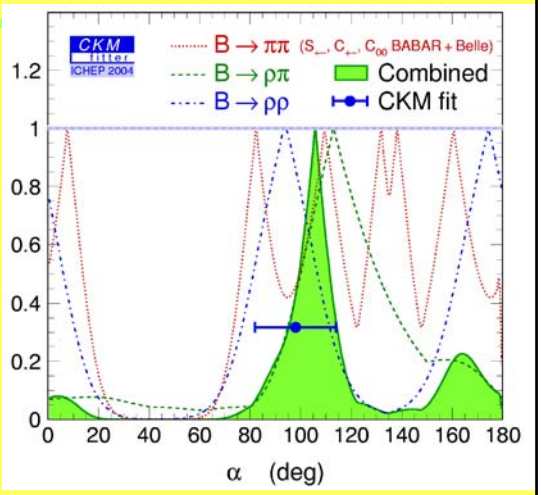
CKM Matrix – ϕ_2

backup slide

	Belle [152M]	*BABAR* [213M]
$A_{CP}^{\rho\pi}$	$-0.16^{+0.09}_{-0.10}$	$-0.088 \pm 0.049 \pm 0.013$
S	$-0.28 \pm 0.23^{+0.10}_{-0.08}$	$-0.10 \pm 0.14 \pm 0.04$
C	$0.25 \pm 0.17^{+0.02}_{-0.06}$	$0.34 \pm 0.11 \pm 0.05$
A^{+-}	$-0.02 \pm 0.16^{+0.05}_{-0.02}$	$-0.21 \pm 0.11 \pm 0.04$
A^{+0}	$-0.53 \pm 0.29^{+0.09}_{-0.04}$	$-0.47 \pm 0.15 \pm 0.06$
	combined 3.6σ	
	$\alpha = (102 \pm 11 \pm 15)^\circ$	$\alpha = (113^{+27}_{-17} \pm 6)^\circ$

[Based on factorization & SU(3); Gronau & Zupan]

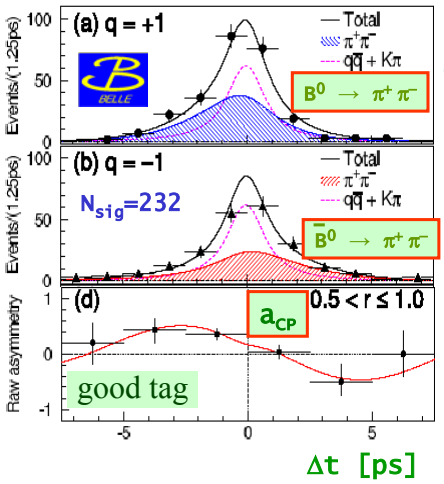
M.A.Giorgi,ICHEP'04



CPV in $B^0 \to \pi^+ \pi^-$: BaBar and Belle, 2004 status

152M $B\bar{B}$ PRL93,021801(2004)

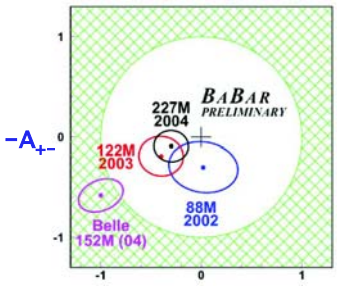
$S_{+-} = -1.00 \pm 0.21 \pm 0.07$
$A_{+-} = 0.58 \pm 0.21 \pm 0.07$



227M $B\bar{B}$ Babar,M.Cristinziani,ICHEP'04

$S_{+-} = -0.30 \pm 0.17 \pm 0.03$
$A_{+-} = 0.09 \pm 0.15 \pm 0.04$

N_{sig}=467



M.A.Giorgi, ICHEP'04