FPCP 2010

Measurements of ϕ_2

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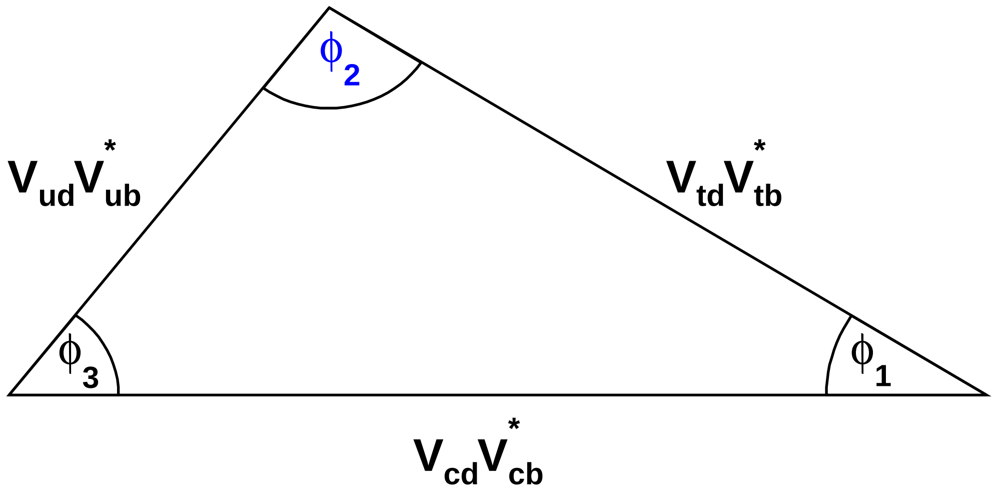
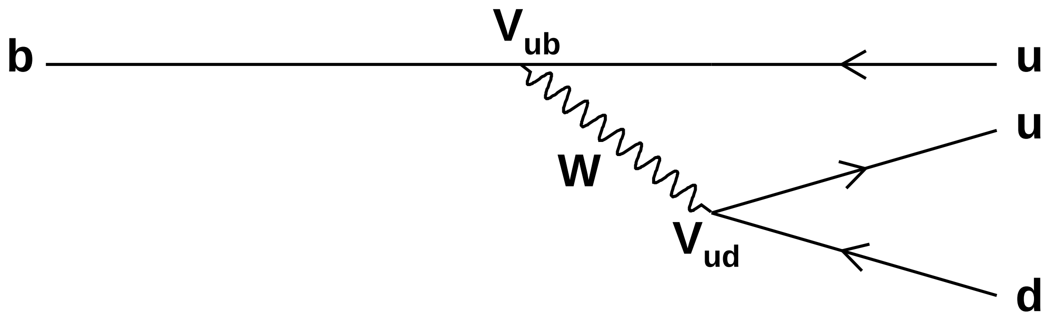
Outline

1. $B^0 \longrightarrow \pi^+\pi^-$
2. $B^0 \longrightarrow (\rho\pi)^0$
3. $B \longrightarrow \rho\rho$
4. $B^0 \longrightarrow a_1(1260)^{\pm}\pi^{\mp}$

From CKM matrix unitarity,

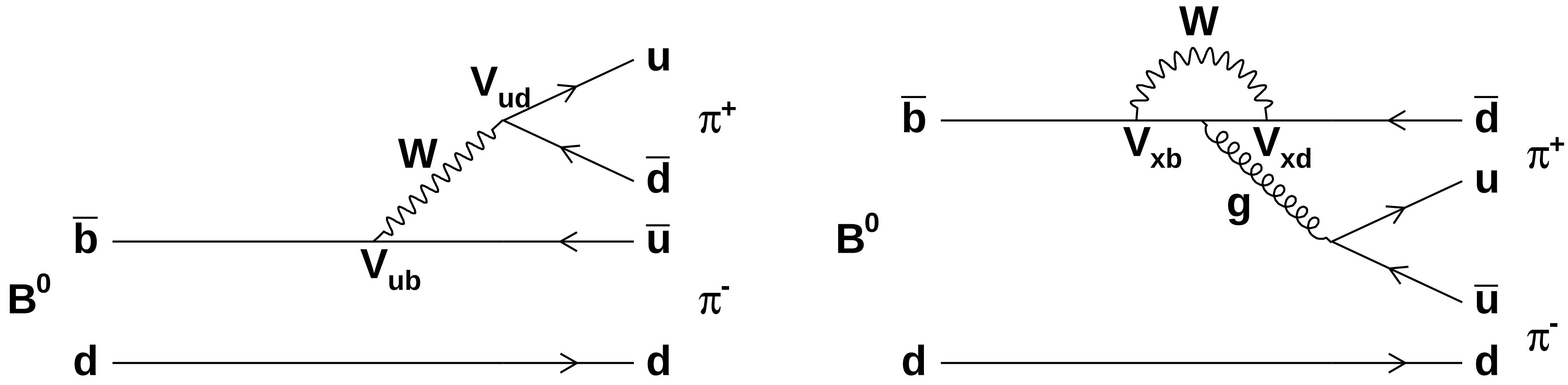


Tree-level $b \longrightarrow u\bar{u}d$ transitions sensitive to ϕ_2



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

Both tree and penguin amplitudes may contribute to the final state



Tree and penguin amplitudes have different strong and weak phases

Direct CP violation, $\mathcal{A}_{CP} \neq 0$, possible

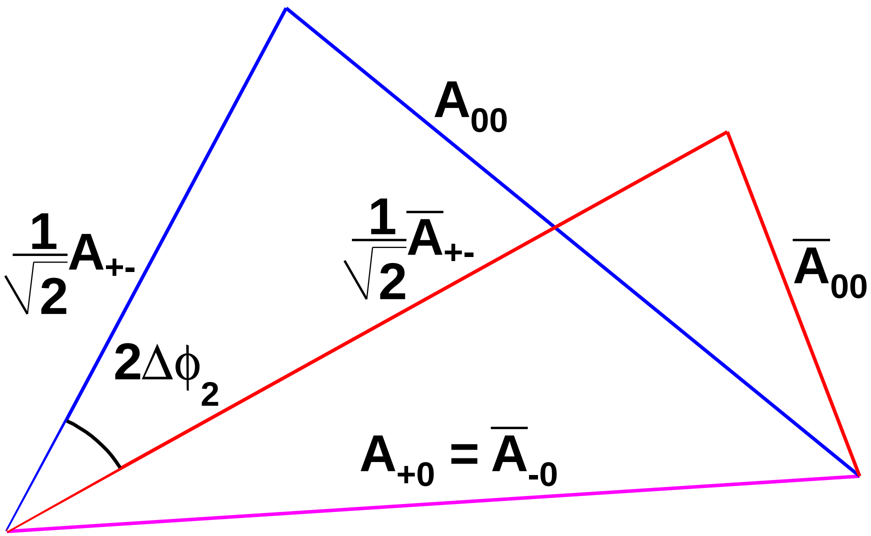
Measure an effective ϕ_2

$$\mathcal{S}_{CP} = \sqrt{1-\mathcal{A}_{CP}^2}\sin(2\phi_2 - 2\Delta\phi_2) = \sqrt{1-\mathcal{A}_{CP}^2}\sin 2\phi_2^{\mathrm{eff}}$$

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

Can recover ϕ_2 with an SU(2) isospin analysis

M. Gronau and D. London, PRL **65**, 3381 (1990)



$$A_{+0} = \frac{1}{\sqrt{2}}A_{+-} + A_{00}$$

$$\bar{A}_{-0} = \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00}$$

A_{ij}: Amplitude of $B \to \pi^i\pi^j$

$B^+ \to \pi^+\pi^0$ is a pure tree mode

Neglecting electroweak penguins, $A_{+0} = \bar{A}_{-0}$

4-fold ambiguity in $2\Delta\phi_2$

Fully determined from 6 physical observables

$\mathcal{B}(B^0 \to \pi^+\pi^-)$, $\mathcal{B}(B^0 \to \pi^0\pi^0)$, $\mathcal{B}(B^+ \to \pi^+\pi^0)$

$\mathcal{A}_{CP}(\pi^+\pi^-)$, $\mathcal{S}_{CP}(\pi^+\pi^-)$, $\mathcal{A}_{CP}(\pi^0\pi^0)$

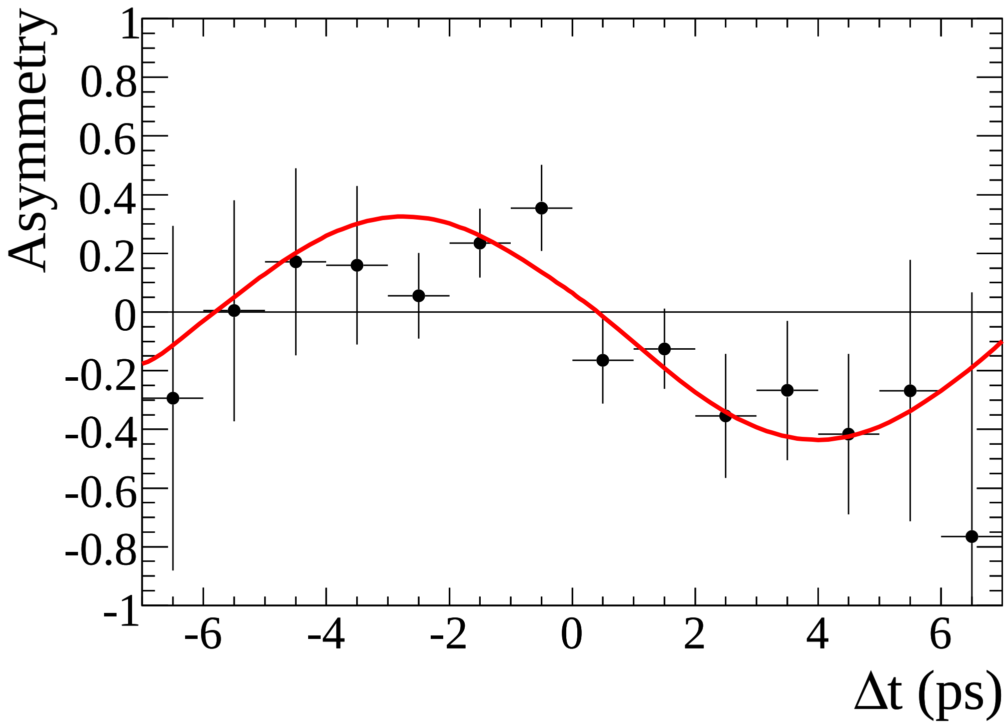
$B^0 \to \pi^+\pi^-$

BaBar

arXiv:0807.4226 (2008)

467 million $B^0\bar{B}^0$ pairs

$A(\Delta t) \equiv (N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$



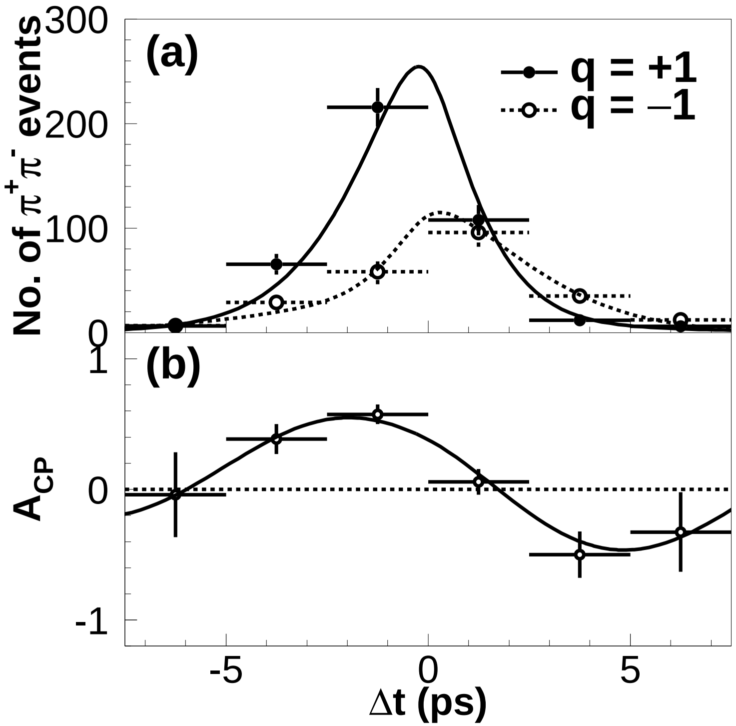
Clear mixing-induced asymmetry

Belle

PRL **98**, 211801 (2007)

535 million $B^0\bar{B}^0$ pairs

Δt distribution and asymmetry



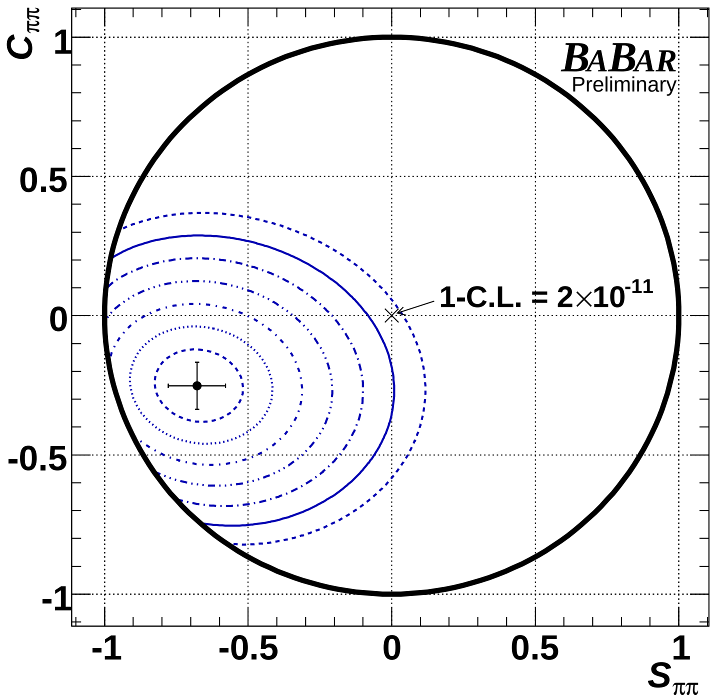
Height difference shows direct CP asymmetry

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

BaBar

$\mathcal{A}_{CP} = +0.25 \pm 0.08 \pm 0.02 \ (3.0\sigma)$

$\mathcal{S}_{CP} = -0.68 \pm 0.10 \pm 0.03 \ (6.3\sigma)$

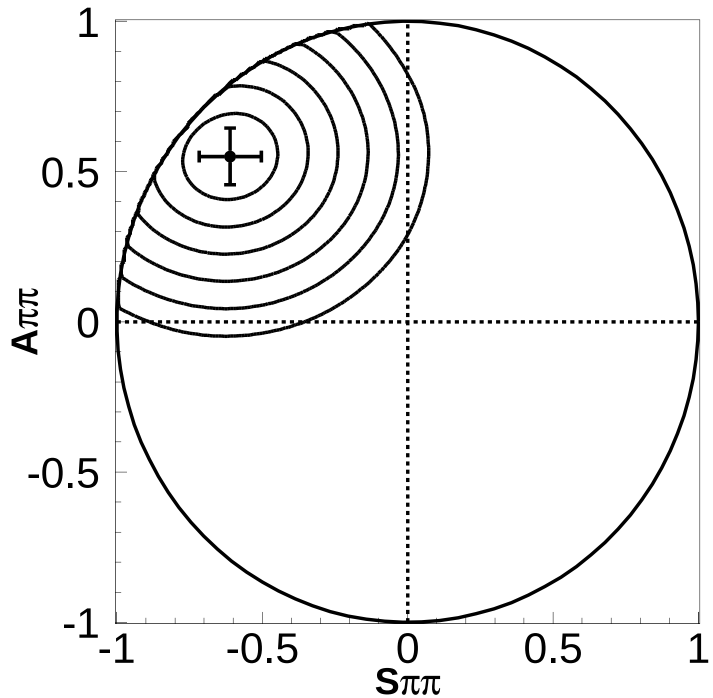


$\mathcal{C}_{CP} = -\mathcal{A}_{CP}$

Belle

$\mathcal{A}_{CP} = +0.55 \pm 0.08 \pm 0.05 \ (5.5\sigma)$

$\mathcal{S}_{CP} = -0.61 \pm 0.10 \pm 0.04 \ (5.3\sigma)$

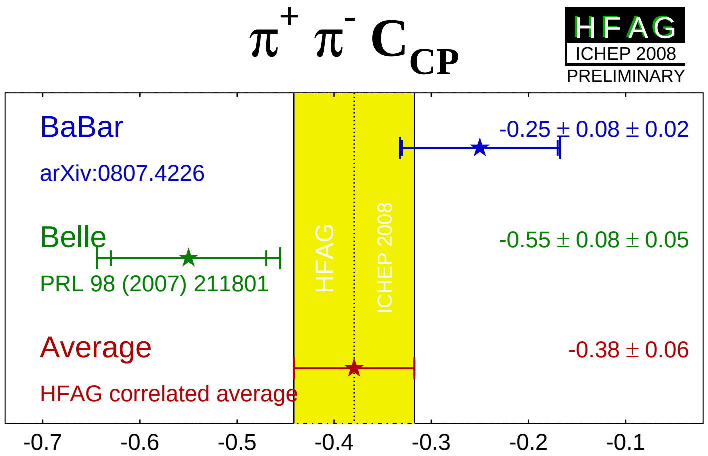


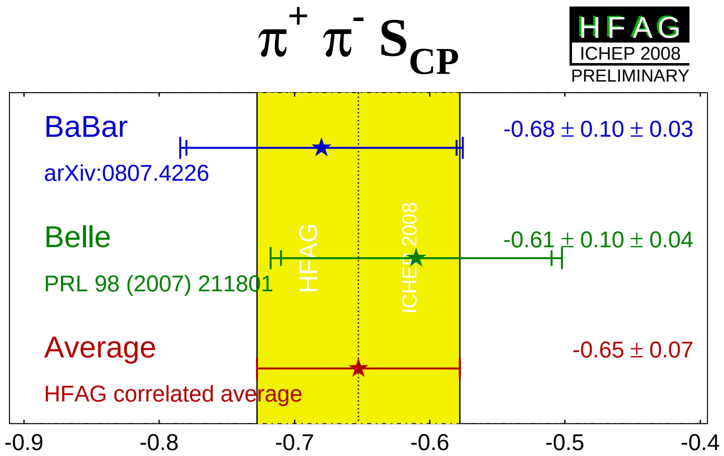
CP violation observed in individual parameters

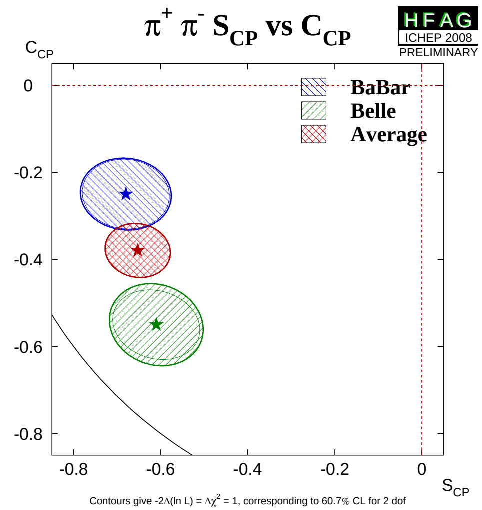
Both experiments have observed CP violation

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

World average







$\mathcal{C}_{CP} = -\mathcal{A}_{CP}$

1.9σ difference between BaBar and Belle measurements

Both experiments demonstrate that more than a tree amplitude is present

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

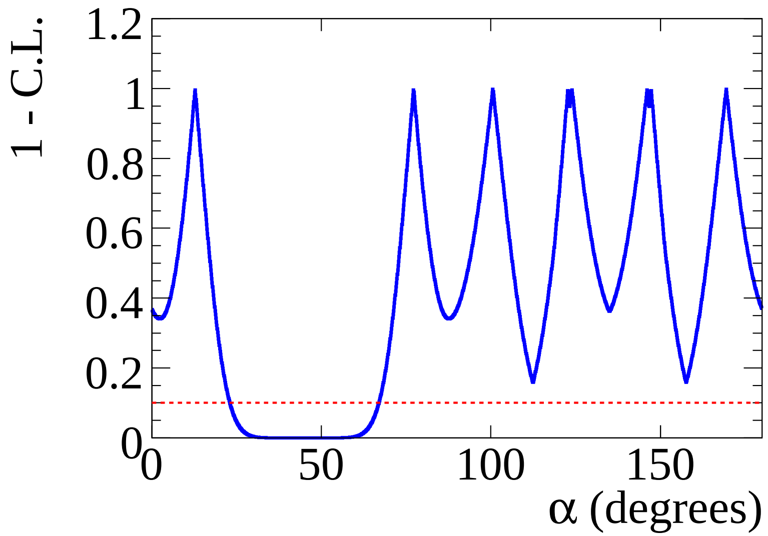
Perform isospin analysis

Scan ϕ_2 and construct χ^2 for the five amplitudes $(A_{+0}, A_{+-}, A_{00}, \bar{A}_{+-}, \bar{A}_{00})$

Convert to CL

BaBar

Use BaBar results only

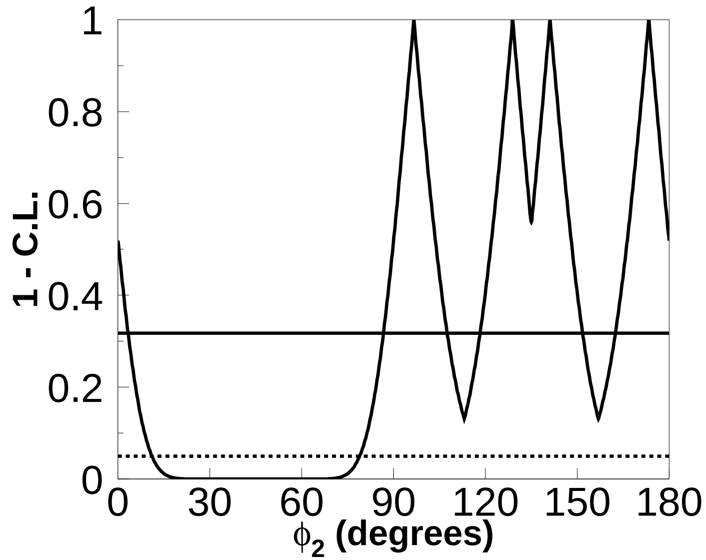


Two-fold ambiguity of ϕ_2^{eff} in $\mathcal{S}_{CP}$ included

$[23^\circ, 67^\circ]$ excluded at 90% CL

Belle

Use Belle results for $\mathcal{A}_{CP}$, $\mathcal{S}_{CP}$, otherwise WA



Only SM expectation of ϕ_2^{eff} in $\mathcal{S}_{CP}$ included

$[11^\circ, 79^\circ]$ excluded at 95% CL

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

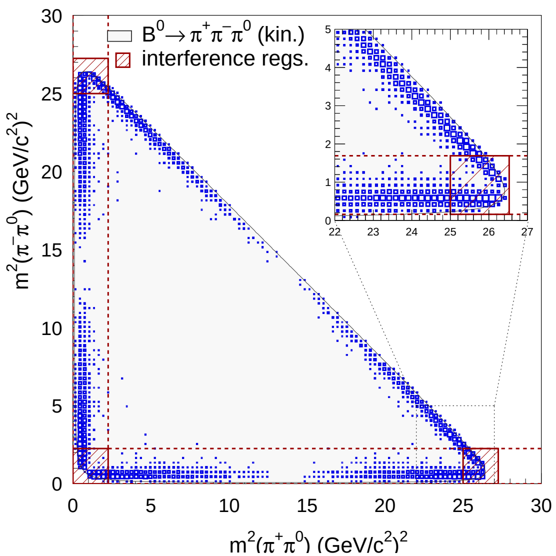
Not a CP eigenstate, need to consider the 4 flavour-charge configurations

Corresponding isospin analysis has 12 unknowns compared to 6 for CP eigenstates

However, can constrain ϕ_2 without ambiguity explicitly in the analysis

A. Snyder and H. Quinn, PRD **48** 2139 (1993)

Include variation of the strong phases of the interfering ρ resonances in the Dalitz Plot



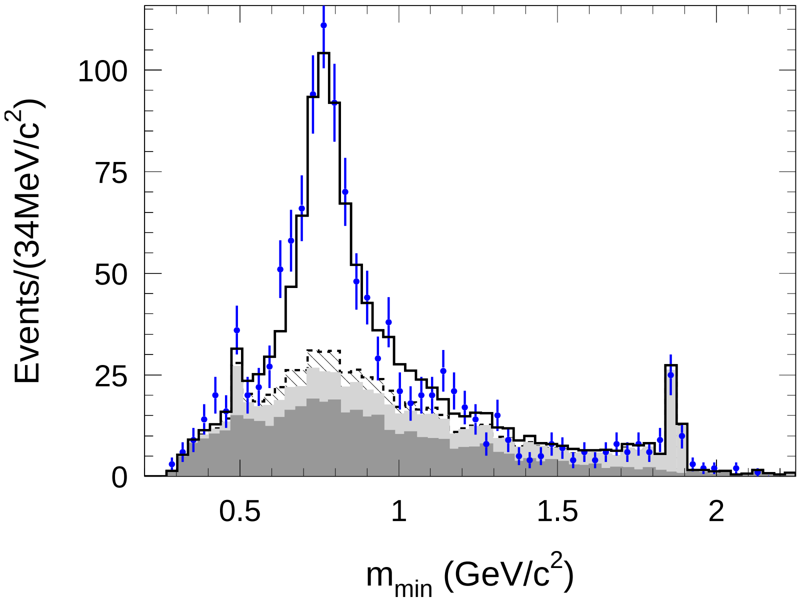
$B^0 \to (\rho\pi)^0$

BaBar

PRD **76** 012004 (2007)

375 million $B^0\bar{B}^0$ pairs

Mass projections



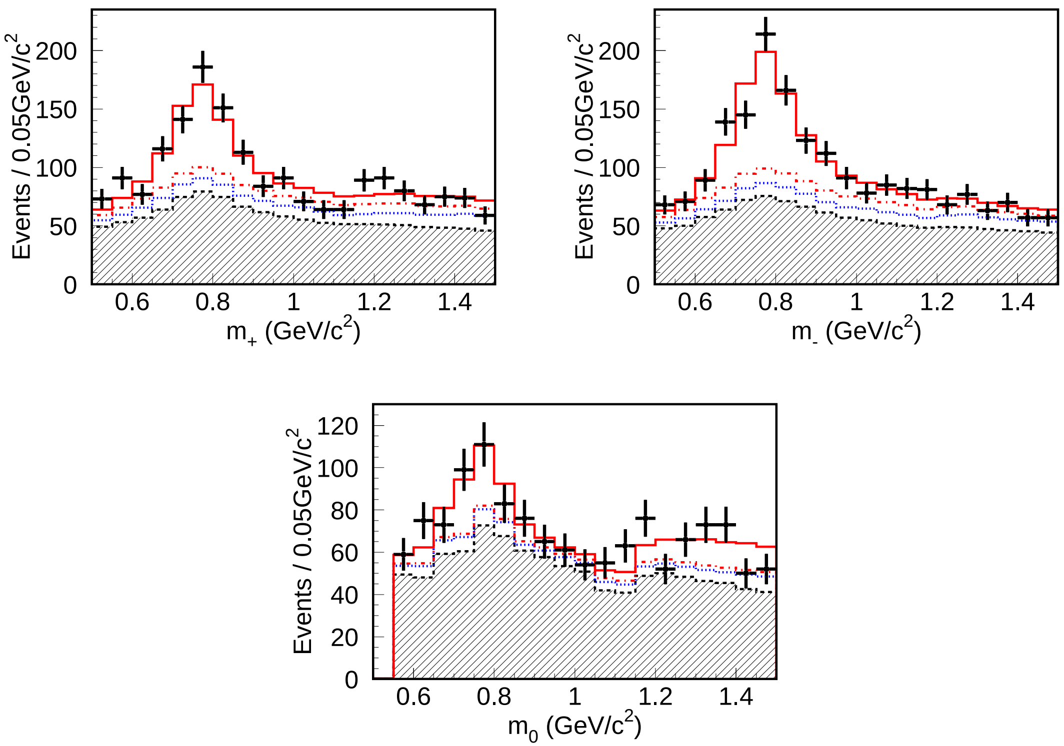
Plot minimum of m_+, m_-, m_0

Belle

PRL **98** 221602 (2007)

449 million $B^0\bar{B}^0$ pairs

Mass projections

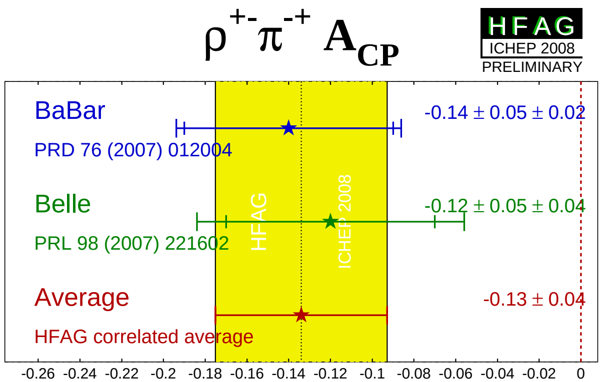


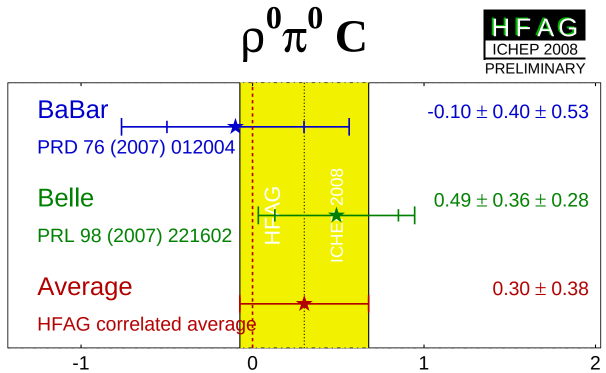
$B^0 \to (\rho\pi)^0$

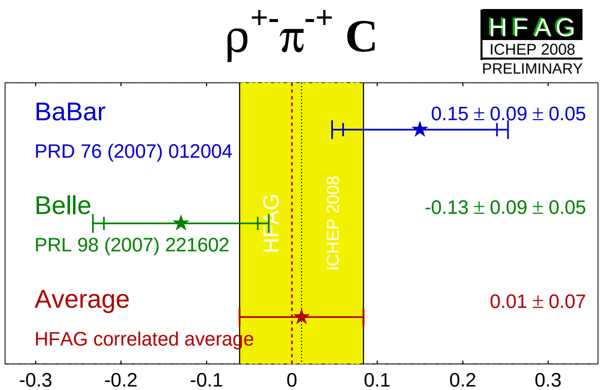
For $B^0 \to \rho^\pm \pi^\mp$

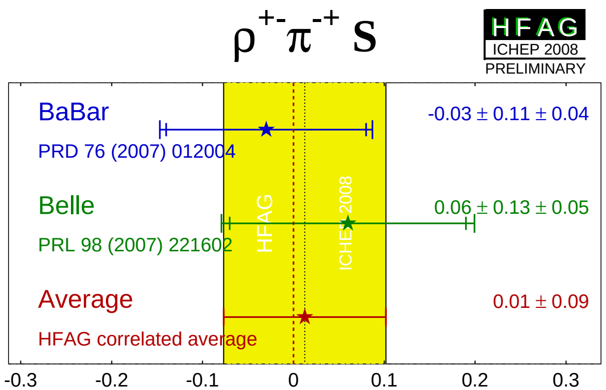
$\mathcal{A}_{CP}$ is time and flavour-integrated CP asymmetry

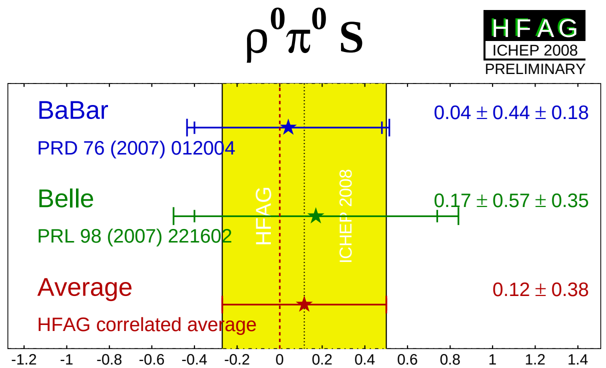
For $B^0 \to \rho^0 \pi^0$











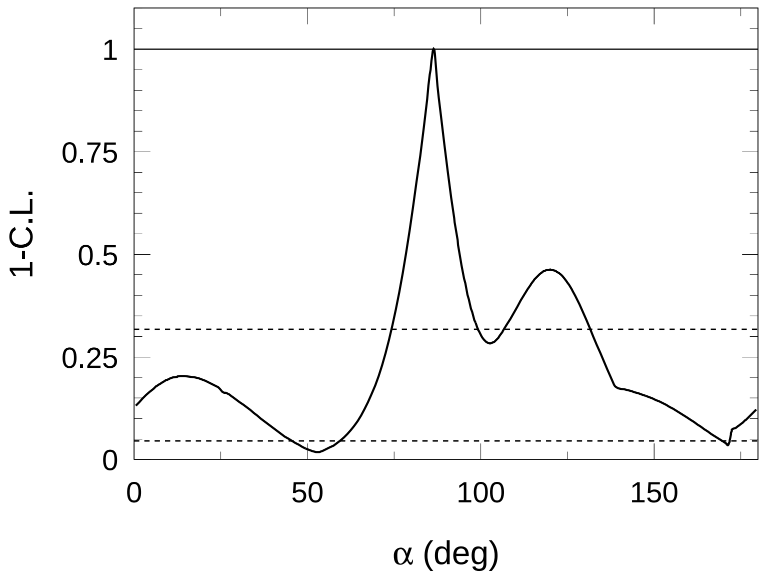
Good agreement between experiments

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

Perform ϕ_2 scan

BaBar

Use $B^0 \to (\rho\pi)^0$ results only

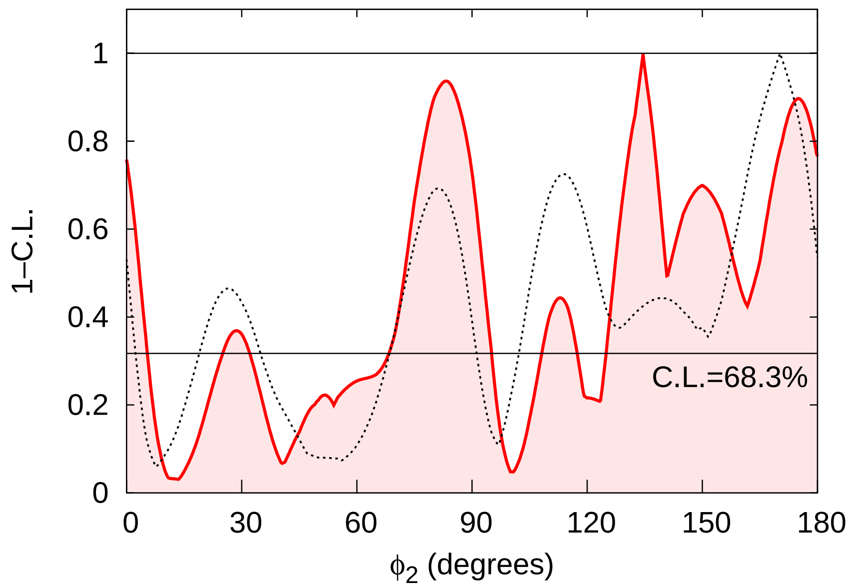


$\phi_2 = (87^{+45}_{-13})^\circ$

for entire ϕ_2 range

Belle

Also include $\mathcal{B}$ and $\mathcal{A}_{CP}$ of $B^+ \to \rho^+\pi^0$, $\rho^0\pi^+$



Dotted line: Use $B^0 \to (\rho\pi)^0$ results only

$68^\circ < \phi_2 < 95^\circ$ at 68.3% CL

for solution consistent with SM

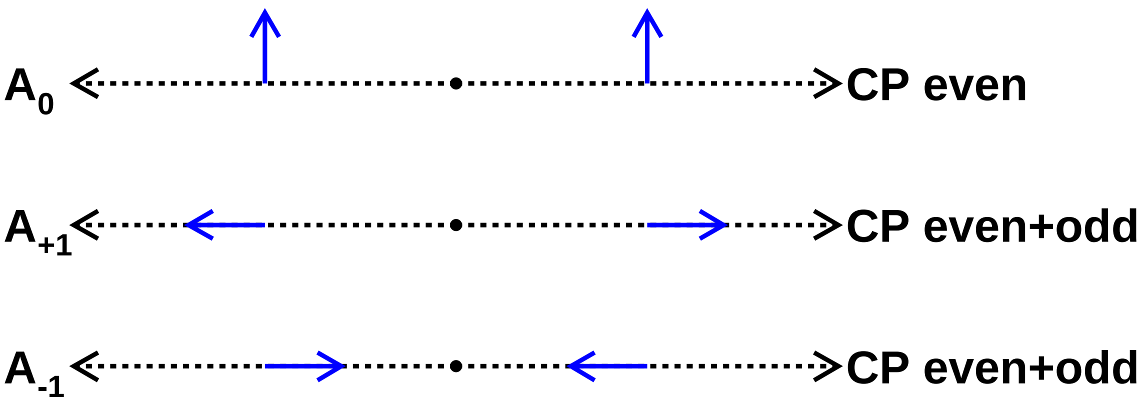
Difficult to pin down ϕ_2 with $B^0 \to (\rho\pi)^0$

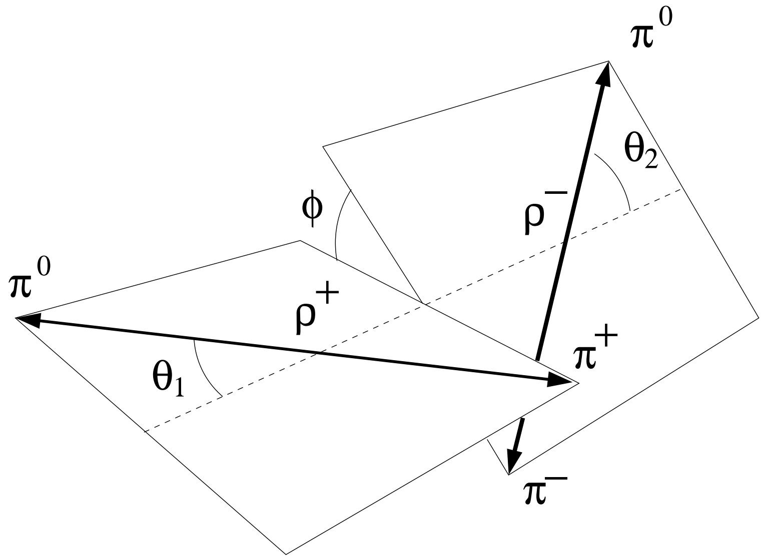
$B^0 \to \rho^+\rho^-$

$S \to VV$

Final state contains 1 longtitudinal and 2 transverse amplitudes

In helicity basis,





Integrating over ϕ, angular decay rate

$$\frac{d^2N}{d\cos\theta_1 d\cos\theta_1} \propto 4f_L\cos^2\theta_1\cos^2\theta_2 + (1-f_L)\sin^2\theta_1\sin^2\theta_2, \quad f_L \equiv \frac{|A_0|^2}{|A_0|^2+|A_{+1}|^2+|A_{-1}|^2}$$

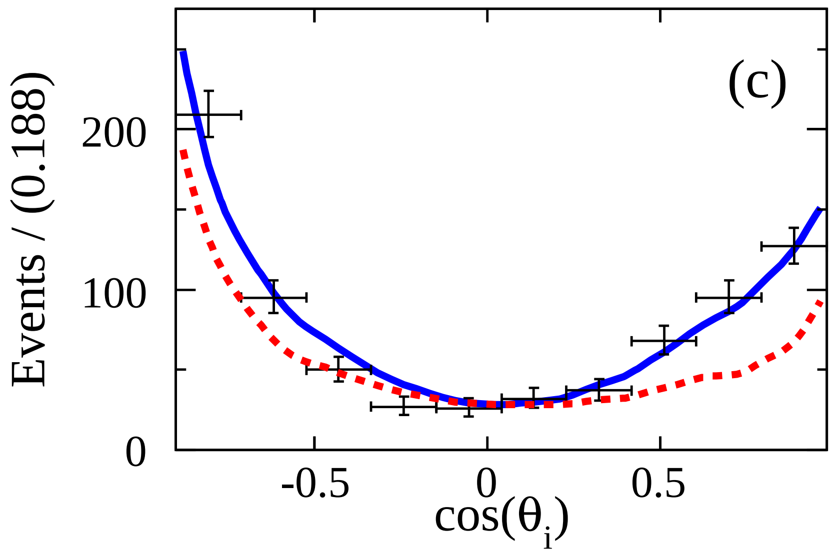
$B^0 \to \rho^+\rho^-$

BaBar

PRD **76** 052007 (2007)

384 million $B^0\bar{B}^0$ pairs

Helicity

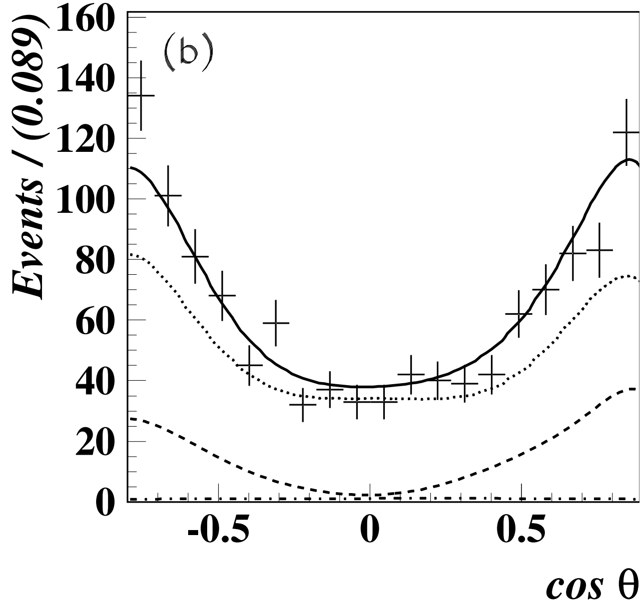


Belle

PRL **96** 171801 (2006)

275 million $B^0\bar{B}^0$ pairs

Helicity



$\mathcal{B}(B^0 \to \rho^+\rho^-) = (25.5 \pm 2.1^{+3.6}_{-3.9}) \times 10^{-6}$

$f_L = 0.992 \pm 0.024\ (\text{stat})^{+0.026}_{-0.013}\ (\text{syst})$

$\mathcal{B}(B^0 \to \rho^+\rho^-) = (22.8 \pm 3.8^{+2.3}_{-2.6}) \times 10^{-6}$

$f_L = 0.941^{+0.034}_{-0.040}\ (\text{stat}) \pm 0.030\ (\text{syst})$

Longtitudinal polarisation dominates

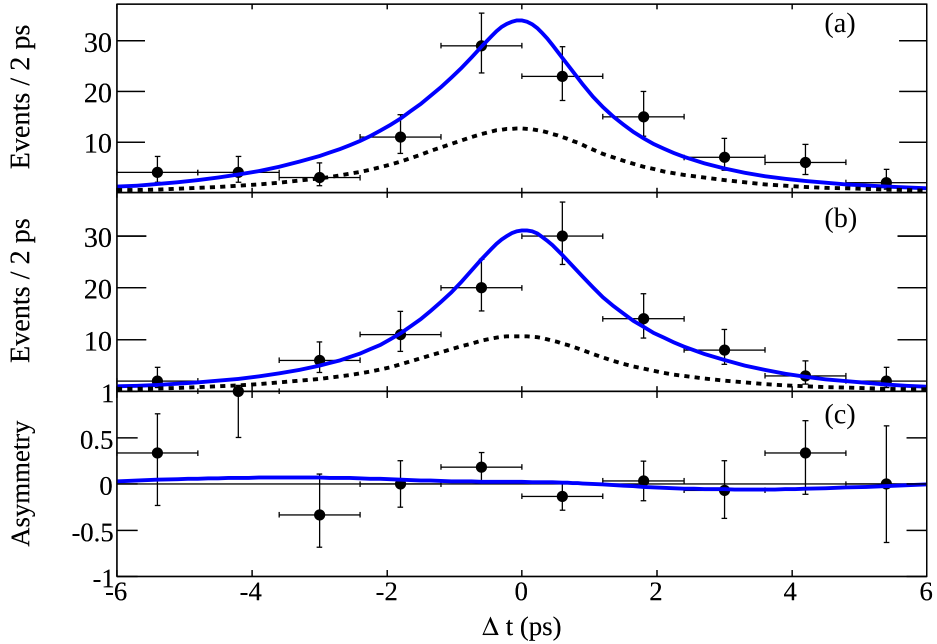
$B^0 \to \rho^+\rho^-$

BaBar

PRD **76** 052007 (2007)

384 million $B^0\bar{B}^0$ pairs

Δt distribution and asymmetry



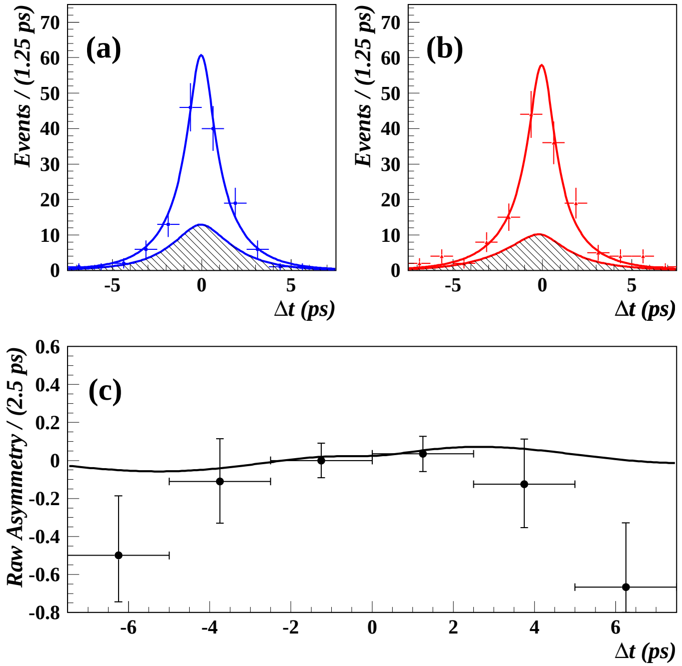
$$\mathcal{A}_{CP} = -0.01 \pm 0.15 \pm 0.06$$
$$\mathcal{S}_{CP} = -0.17 \pm 0.20^{+0.05}_{-0.06}$$

Belle

PRD **76** 011104 (2007)

Update to 535 million $B^0\bar{B}^0$ pairs

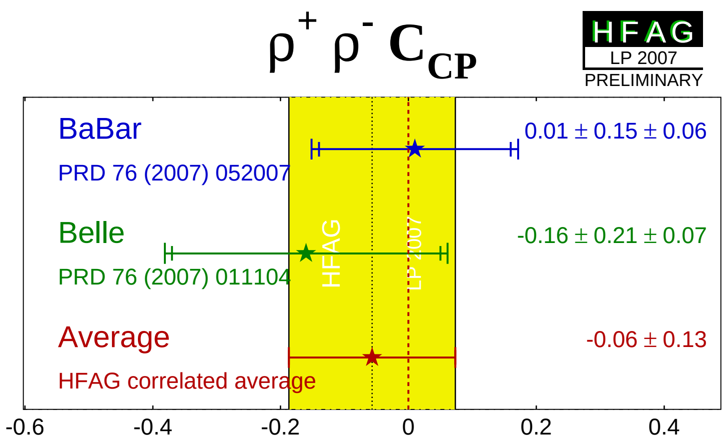
Δt distribution and asymmetry

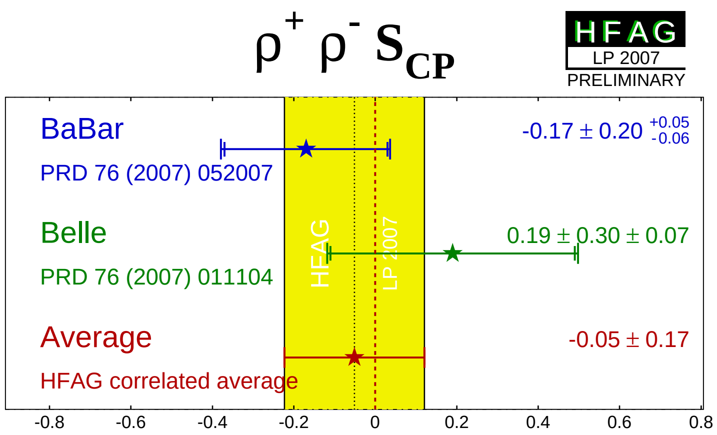


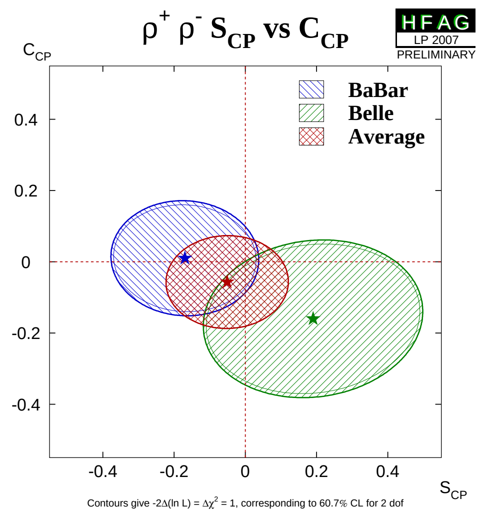
$$\mathcal{A}_{CP} = +0.16 \pm 0.21 \pm 0.07$$
$$\mathcal{S}_{CP} = +0.19 \pm 0.30 \pm 0.07$$

$B^0 \to \rho^+\rho^-$

World average







$\mathcal{C}_{CP} = -\mathcal{A}_{CP}$

Good agreements between experiments

$\mathcal{A}_{CP} \approx 0$, small penguin contribution

$B^0 \to \rho^0 \rho^0$

Time-dependent measurement provides additional information to isospin analysis

BaBar

PRD **78** 071104(R) (2008)

465 million $B^0 \bar{B}^0$ pairs

$\mathcal{B}(B^0 \to \rho^0 \rho^0) =$

$$(0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$$

3.1σ evidence

$f_L = 0.75^{+0.11}_{-0.14}\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst})$

$\mathcal{A}_{CP} = -0.2 \pm 0.8 \pm 0.3$

$\mathcal{S}_{CP} = +0.3 \pm 0.7 \pm 0.2$

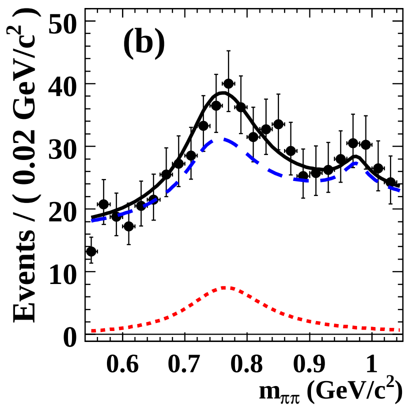
Belle

PRD **78** 111102(R) (2008)

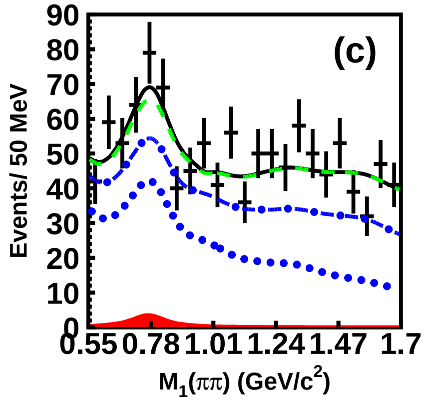
657 million $B^0 \bar{B}^0$ pairs

$\mathcal{B}(B^0 \to \rho^0 \rho^0) < 1.0 \times 10^{-6}$ at 90% CL

BaBar



Belle



Difficult to isolate $\rho^0 \rho^0$ in presence of other 4-body signals, $a_1\pi, \rho\pi\pi, 4\pi, f_0\rho^0, f_0 f_0, f_0\pi\pi$

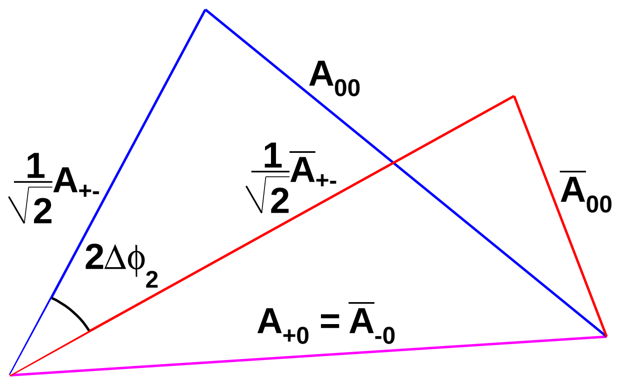
$B^+ \to \rho^+ \rho^0$

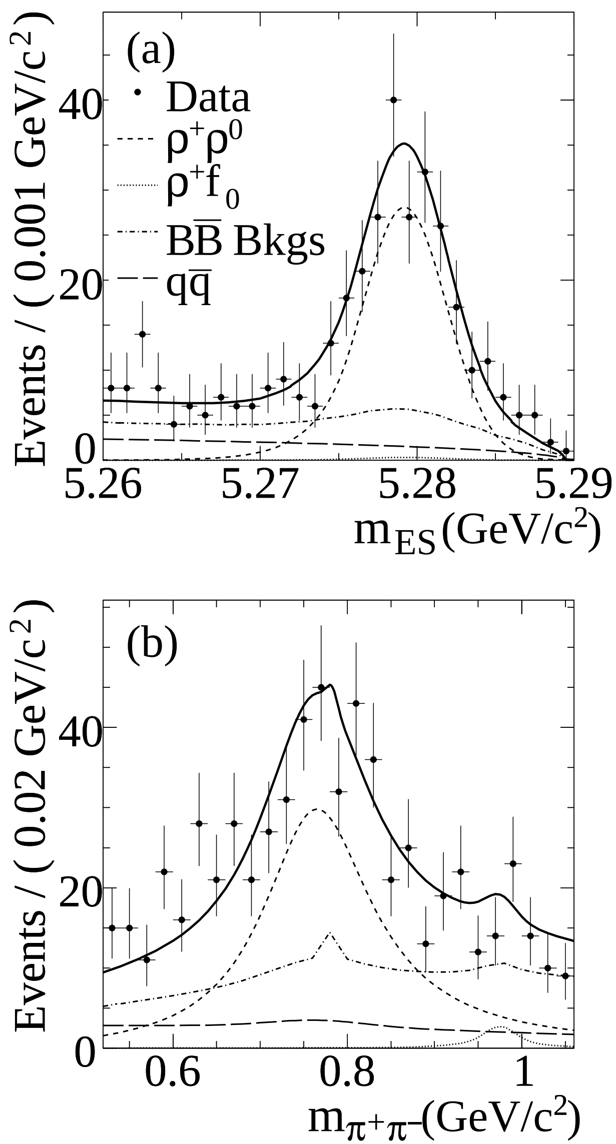
Recent results from BaBar

PRL **102** 141802 (2009)

$\mathcal{B}(B^+ \to \rho^+ \rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$

Precise measurement of isospin triangle base





$f_L = 0.950 \pm 0.015 \pm 0.006$

Dominantly longtitudinally polarised

$\mathcal{A}_{CP} = 0.054 \pm 0.055 \pm 0.010$

No evidence for electroweak penguins

$B^0 \to \rho\rho$

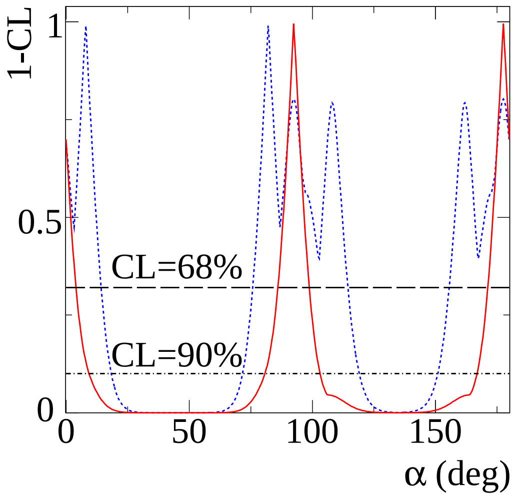
Branching fraction of $B^+ \to \rho^+\rho^0$ large compared to $B^0 \to \rho^0\rho^0$

Nearly flat isospin traingles $\Rightarrow$ 4 solutions of $\Delta\phi_2$ nearly degenerate

BaBar

PRL **102** 141802 (2009)

Use BaBar results only



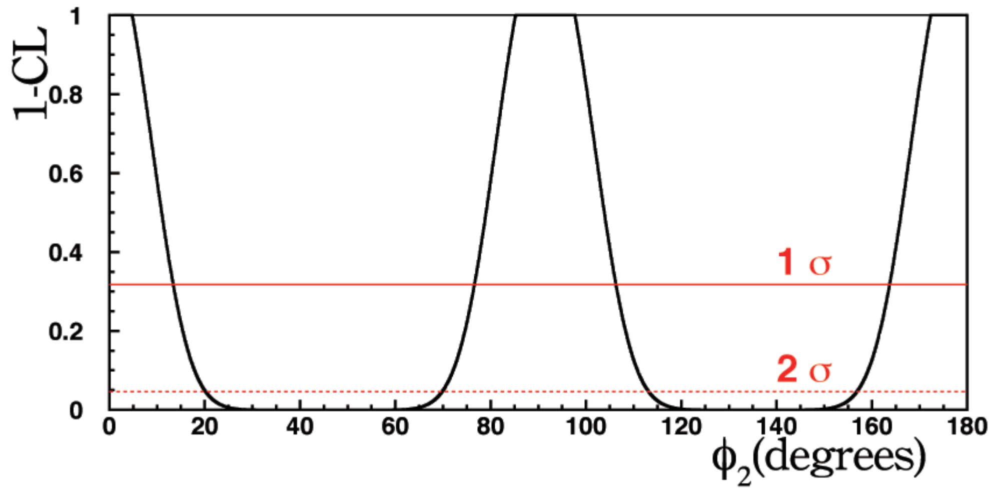
Blue: Before $\mathcal{B}(B^+ \to \rho^+\rho^0)$ increase

$$\phi_2 = (92.4^{+6.0}_{-6.5})^\circ$$

Belle

Use Belle results for $\mathcal{B}(\rho^0\rho^0)$, otherwise WA

Before BaBar's $B^+ \to \rho^+\rho^0$ update



Plateau due to no constraint on $\mathcal{A}_{CP}(\rho^0\rho^0)$

$$\phi_2 = (91.7 \pm 14.9)^\circ$$

$B \to \rho\rho$ the best environment for constraining ϕ_2 because of relatively small penguins

$B^0 \to a_1(1260)^{\pm}\pi^{\mp}$

Not a CP eigenstate, need to consider the 4 flavour-charge configurations

$$\mathcal{P}_{a_1\pi}(\Delta t, q, c) = (1 + c\mathcal{A}_{CP}) \frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}} \Big\{ 1 + q \times \Big[(\mathcal{S}_{CP} + c\Delta\mathcal{S}) \sin \Delta m_d \Delta t - (\mathcal{C}_{CP} + c\Delta\mathcal{C}) \cos \Delta m_d \Delta t \Big] \Big\}$$

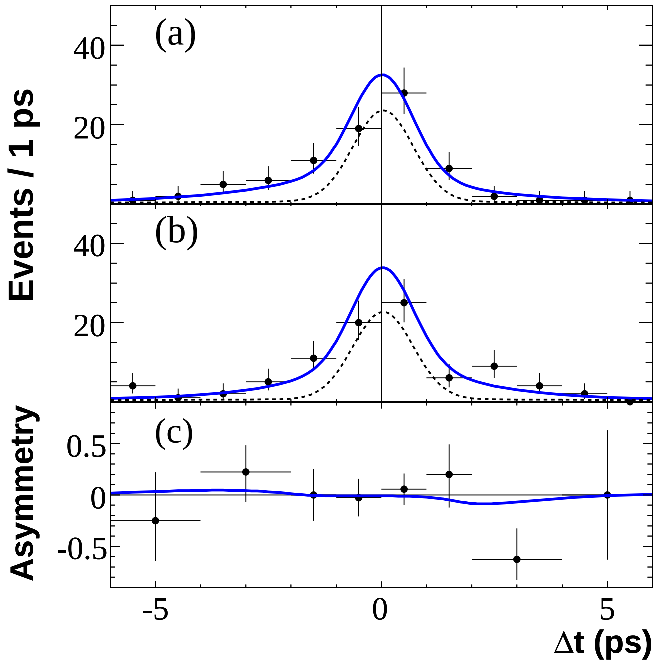
$q = \pm 1$: flavour tag, $c = \pm 1$: a_1 charge

Only $\mathcal{A}_{CP}, \mathcal{C}_{CP}$ and $\mathcal{S}_{CP}$ sensitive to CP violation

BaBar: 384 million $B^0\bar{B}^0$ pairs

$$\mathcal{A}_{CP} = -0.07 \pm 0.07\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$
$$\mathcal{C}_{CP} = -0.10 \pm 0.15\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst})$$
$$\mathcal{S}_{CP} = +0.37 \pm 0.21\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$$
$$\Delta\mathcal{C} = +0.26 \pm 0.15\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$$
$$\Delta\mathcal{S} = -0.14 \pm 0.21\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})$$

PRL **98** 181803 (2007)



$B \to K_{1A}\pi$

4-fold ambiguity for ϕ_2^{eff}

$$\phi_2^{\text{eff}} = \frac{1}{4}\left[\arcsin\left(\frac{\mathcal{S}_{CP}+\Delta\mathcal{S}}{\sqrt{1-(\mathcal{C}_{CP}+\Delta\mathcal{C})^2}}\right)+\arcsin\left(\frac{\mathcal{S}_{CP}-\Delta\mathcal{S}}{\sqrt{1-(\mathcal{C}_{CP}-\Delta\mathcal{C})^2}}\right)\right]$$

Can measure $|\Delta\phi_2|$ using $SU(3)$ symmetry involving $B^0 \to a_1 K$, $B \to K_{1A}\pi$ decays

M. Gronau and J. Zupan, PRD **73** 057502 (2006)

PRD **81** 052009 (2010)

New result from BaBar, 454 million $B^0\bar{B}^0$ pairs

Amplitude analysis of WA3 data taken by ACCMOR collaboration

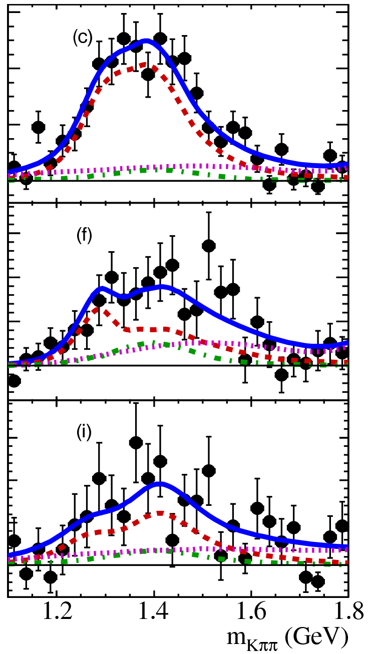
Needed to determine $K\pi\pi$ model

First measurement!

$$\mathcal{B}(B^0 \to K_1(1270)^+\pi^- + K_1(1400)^+\pi^-) = 3.1^{+0.8}_{-0.7}\times 10^{-5}\ (7.5\sigma)$$

$$\mathcal{B}(B^+ \to K_1(1270)^0\pi^+ + K_1(1400)^0\pi^+) = 2.9^{+2.9}_{-1.7}\times 10^{-5}\ (3.2\sigma)$$

Relative contributions also determined



$B \to K_{1A}\pi$

Solve system of inequalities,

$$\cos 2(\phi^{\pm}_{2,\,\mathrm{eff}} - \phi_2) \geq \frac{1 - 2R^0_{\pm}}{\sqrt{1 - \mathcal{A}^{\pm\,2}_{CP}}}$$

$$\cos 2(\phi^{\pm}_{2,\,\mathrm{eff}} - \phi_2) \geq \frac{1 - 2R^+_{\pm}}{\sqrt{1 - \mathcal{A}^{\pm\,2}_{CP}}}$$

$$R^0_+ \equiv \frac{\bar{\lambda}^2 f^2_{a_1} \bar{\Gamma}(K^+_{1A}\pi^-)}{f^2_{K_{1A}} \bar{\Gamma}(a^+_1\pi^-)}, \quad R^0_- \equiv \frac{\bar{\lambda}^2 f^2_{\pi} \bar{\Gamma}(a^-_1 K^+)}{f^2_{K} \bar{\Gamma}(a^-_1\pi^+)}$$

$$R^+_+ \equiv \frac{\bar{\lambda}^2 f^2_{a_1} \bar{\Gamma}(K^0_{1A}\pi^+)}{f^2_{K_{1A}} \bar{\Gamma}(a^+_1\pi^-)}, \quad R^+_- \equiv \frac{\bar{\lambda}^2 f^2_{\pi} \bar{\Gamma}(a^+_1 K^0)}{f^2_{K} \bar{\Gamma}(a^-_1\pi^+)}$$

$$\lambda^2 = |V_{us}|/|V_{ud}| = |V_{cd}|/|V_{cs}|$$

$\bar{\Gamma}$: averaged decay rates, f_i: decay constants

Calculate bound on $|\Delta\phi_2| \equiv |\phi^{\mathrm{eff}}_2 - \phi_2|$ from

$$|\phi^{\mathrm{eff}}_2 - \phi_2| \leq (|\phi^+_{2,\,\mathrm{eff}} - \phi_2| + |\phi^-_{2,\,\mathrm{eff}} - \phi_2|)/2$$

$|\Delta\phi_2| < 11^\circ(13^\circ)$ at 68% (90%) CL

Solution nearest SM expectation, $\phi^{\mathrm{eff}}_2 = (79 \pm 7 \pm 11)^\circ$

Summary

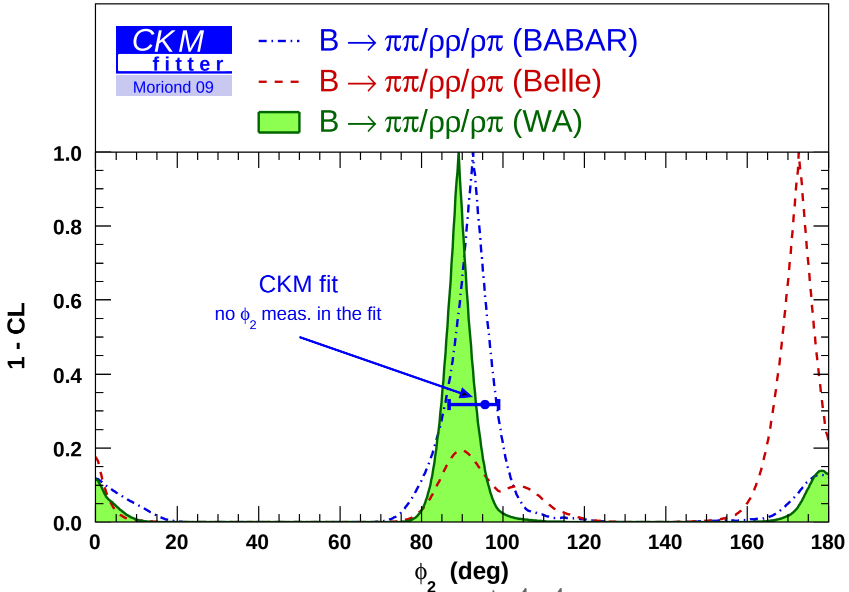
Many measurements of ϕ_2 performed by the B factories

Recent results from BaBar on $B^+ \to \rho^+\rho^0$ and $B \to K_{1A}\pi$

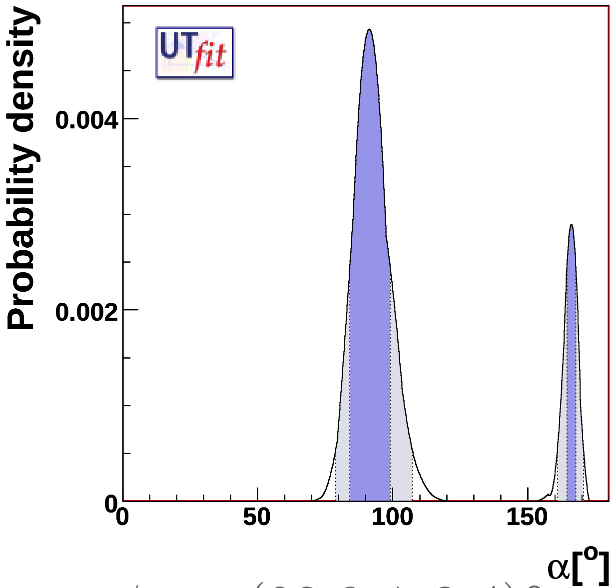
$B \to \rho\rho$ gives tightest constraint on ϕ_2

Both experiments have final data sets taken at $\Upsilon(4S)$ resonance

Many final results still anticipated



$\phi_2 = (89.0^{+4.4}_{-4.2})^\circ$



$\phi_2 = (92.0 \pm 3.4)^\circ$

Backup

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

Time and amplitude differential decay rate,

$$\frac{d^3\Gamma}{d\Delta t ds_+ ds_-} \propto e^{-|\Delta t|/\tau_{B^0}} \Big\{ (|A_{3\pi}|^2 + |\bar{A}_{3\pi}|^2) - q(|A_{3\pi}|^2 - |\bar{A}_{3\pi}|^2) \cos \Delta m_d \Delta t + 2q \Im \left[\frac{q}{p} A^*_{3\pi} \bar{A}_{3\pi} \right] \sin \Delta m_d \Delta t \Big\}$$

$$|A_{3\pi}|^2 \pm |\bar{A}_{3\pi}|^2 = \sum_{\kappa \in \{+,-,0\}} |f_\kappa|^2 U^{\pm}_\kappa + \sum_{\kappa < \sigma \in \{+,-,0\}} 2(\Re[f_\kappa f^*_\sigma] U^{\pm,\Re}_{\kappa\sigma} - \Im[f_\kappa f^*_\sigma] U^{\pm,\Im}_{\kappa\sigma})$$

$$\Im \left[\frac{q}{p} A^*_{3\pi} \bar{A}_{3\pi} \right] = \sum_{\kappa \in \{+,-,0\}} |f_\kappa|^2 I_\kappa + \sum_{\kappa < \sigma \in \{+,-,0\}} (\Re[f_\kappa f^*_\sigma] I^{\Im}_{\kappa\sigma} + \Im[f_\kappa f^*_\sigma] I^{\Re}_{\kappa\sigma})$$

27 coefficients U, I determined from a fit to data

f: Form factors and line shapes

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

Convert to Quasi-two-body parameters

For $B^0 \to \rho^\pm \pi^\mp$

$$\mathcal{A}_{CP} = \frac{U_+^+ - U_-^+}{U_+^+ + U_-^+}$$

$$\mathcal{C}_{CP} = \frac{1}{2}\left(\frac{U_+^-}{U_+^+} + \frac{U_-^-}{U_-^+}\right), \quad \mathcal{S}_{CP} = \frac{I_+}{U_+^+} + \frac{I_-}{U_-^+}$$

$$\Delta\mathcal{C} = \frac{1}{2}\left(\frac{U_+^-}{U_+^+} - \frac{U_-^-}{U_-^+}\right), \quad \Delta\mathcal{S} = \frac{I_+}{U_+^+} - \frac{I_-}{U_-^+}$$

For $B^0 \to \rho^0 \pi^0$

$$\mathcal{A}_{CP} = -\frac{U_0^-}{U_0^+}, \quad \mathcal{S}_{CP} = \frac{2I_0}{U_0^+}$$

$$U_\kappa^\pm = |A_\kappa|^2 \pm |\bar{A}_\kappa|^2$$

$$U_{\kappa\sigma}^{\pm,\Re} = \Re[A_\kappa A_\sigma^* \pm \bar{A}_\kappa \bar{A}_\sigma^*]$$

$$U_{\kappa\sigma}^{\pm,\Im} = \Im[A_\kappa A_\sigma^* \pm \bar{A}_\kappa \bar{A}_\sigma^*]$$

$$I_\kappa = \Im[\bar{A}_\kappa A_\kappa^*]$$

$$I_{\kappa\sigma}^{\Re} = \Re[\bar{A}_\kappa A_\sigma^* - \bar{A}_\sigma A_\kappa^*]$$

$$I_{\kappa\sigma}^{\Im} = \Im[\bar{A}_\kappa A_\sigma^* + \bar{A}_\sigma A_\kappa^*]$$

$$e^{+2i\phi_2} = \frac{\bar{A}_+ + \bar{A}_- + 2\bar{A}_0}{A_+ + A_- + 2A_0}$$