Measurement of ϕ_2 in $B \to \pi\pi$, $\rho\pi$ and $\rho\rho$

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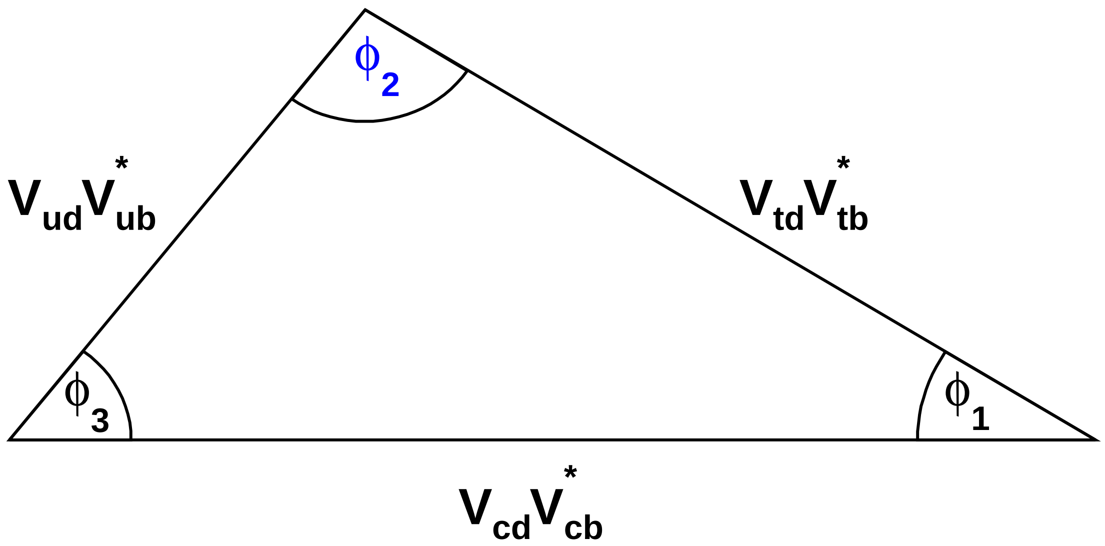
Outline

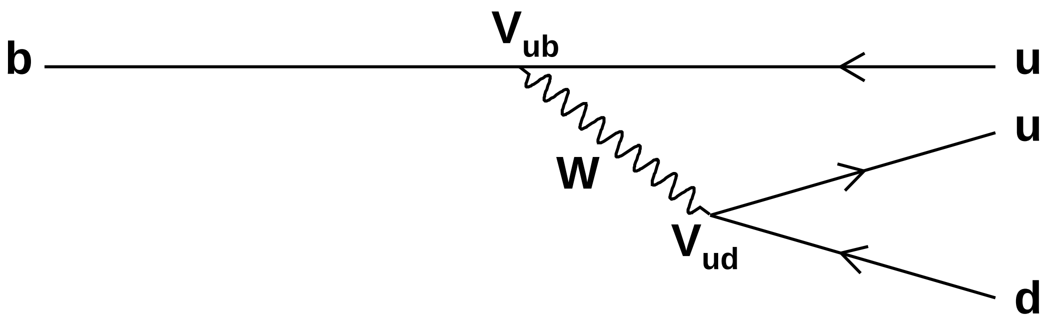
1. $B \longrightarrow \pi\pi$
2. $B \longrightarrow \rho\rho$
3. $B^0 \longrightarrow (\rho\pi)^0$

From unitarity of the CKM matrix,

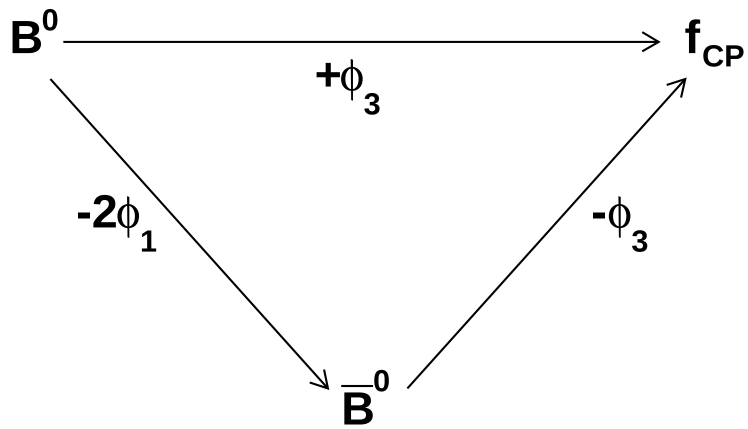


Introduction

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



V_{ub} carries the phase $e^{-i\phi_3}$



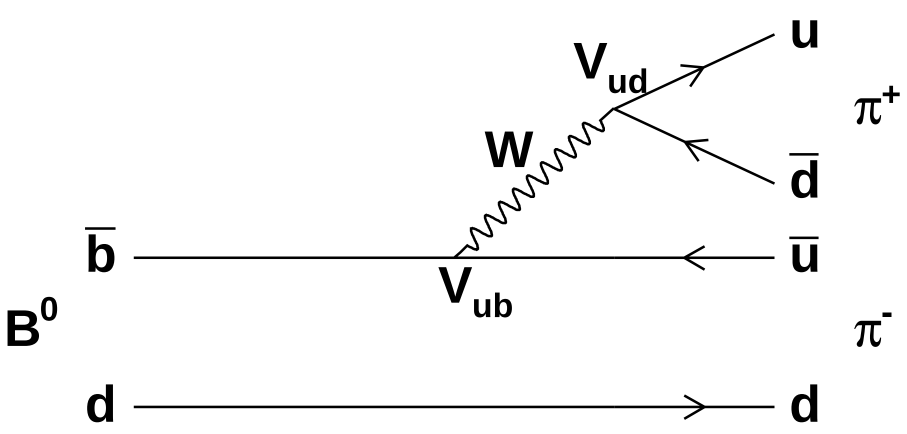
Measure a time difference between B decays, Δt, and the flavour of the tag-side B, q

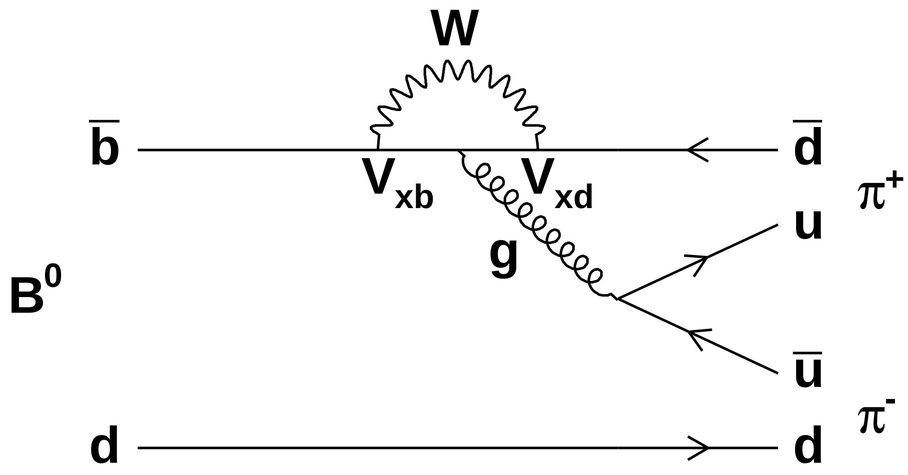
$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q(\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t)\right]$$

If only the tree amplitude is present we expect, $\mathcal{A}_{CP} = 0$, $\mathcal{S}_{CP} = \sin 2\phi_2$

Introduction

Both tree and penguin amplitudes may contribute to the final state





Tree and penguin amplitudes carry different strong and weak phases

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

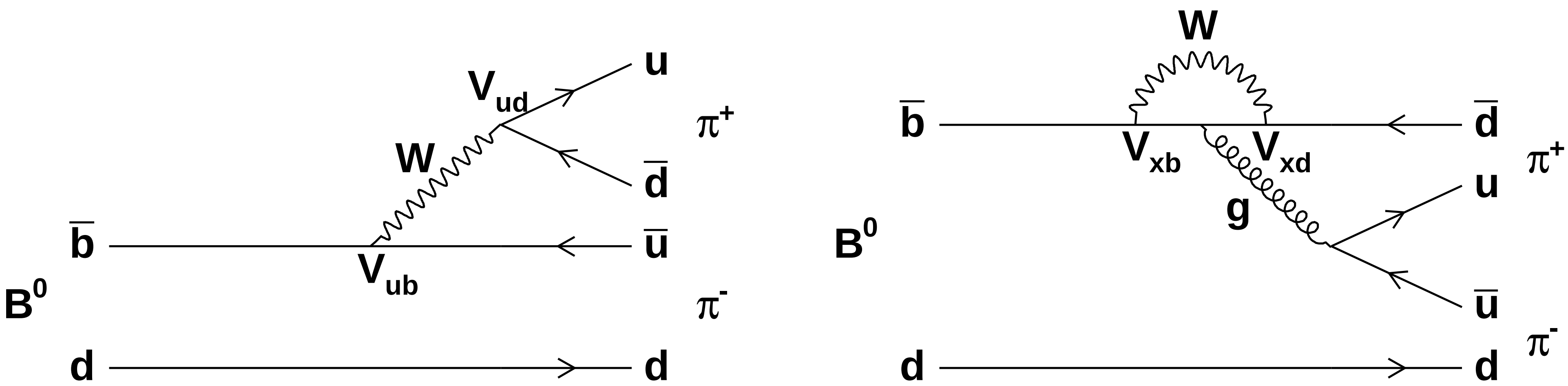
Measure an effective ϕ_2

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

Introduction

Can recover ϕ_2 with an SU(2) isospin analysis

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



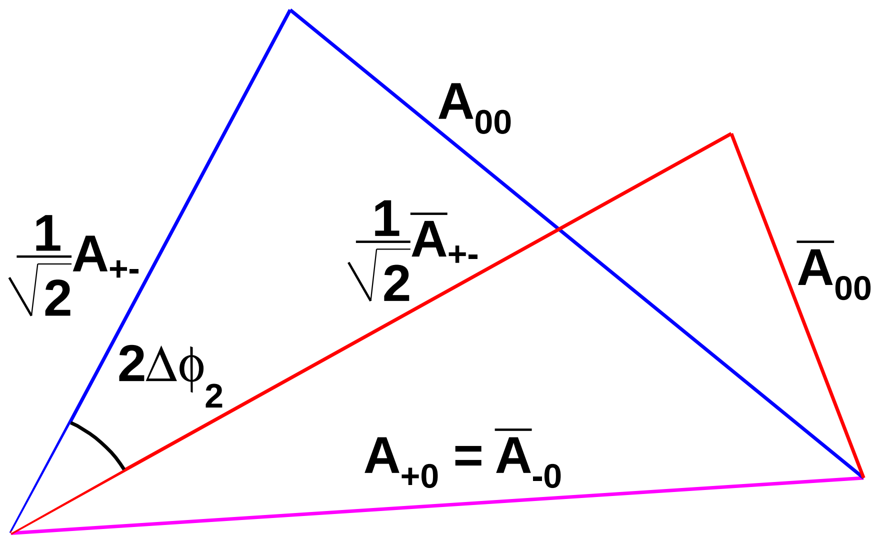
Consider $B^+ \to \pi^+\pi^0$ which has $I_3 = 1 \Rightarrow$ Isospin, $I = 1, 2$

Gluon in penguin carries $I = 0 \Rightarrow$ penguin has $I = 0, 1$

Bose-Einstein statistics forbids anti-symmetric state, $I = 1$

$\Rightarrow I = 2$ and therefore $B^+ \to \pi^+\pi^0$ is a pure tree mode

Introduction



Consider the set of 3 $B \to \pi\pi$ modes

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

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

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

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

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

2-fold ambiguity of ϕ_2 in measured $\mathcal{S}_{CP}$, therefore 8-fold ambiguity in ϕ_2 in isospin analysis

Fully determined from 6 physical observables

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

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

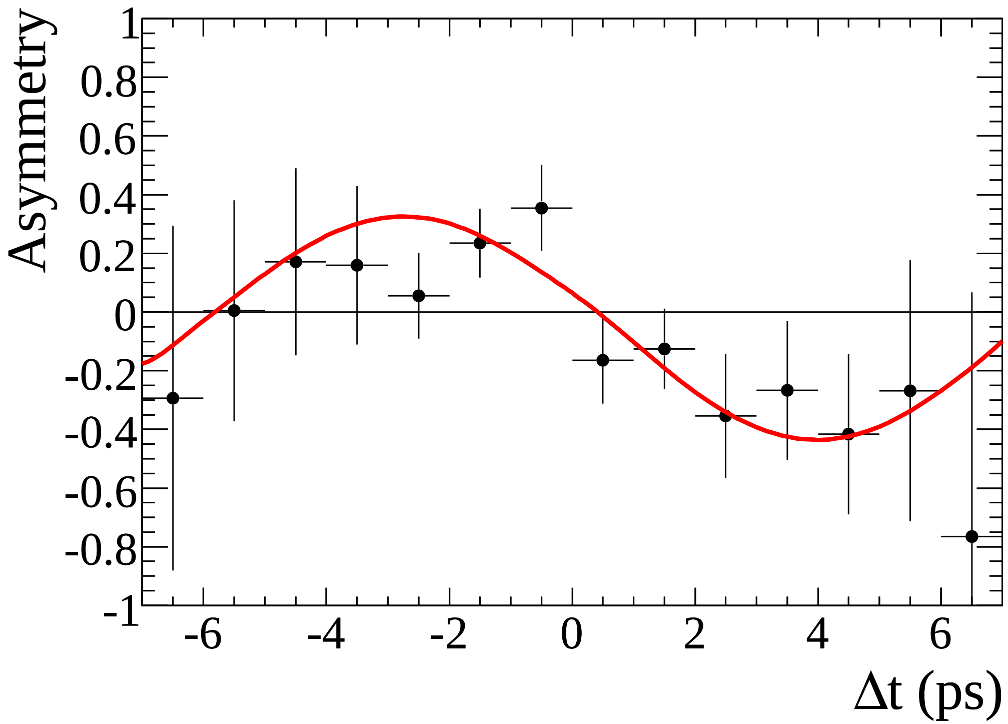
$B \to \pi\pi$

BaBar

arXiv:0807.4226 (2008)

467 million $B\bar{B}$ pairs

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



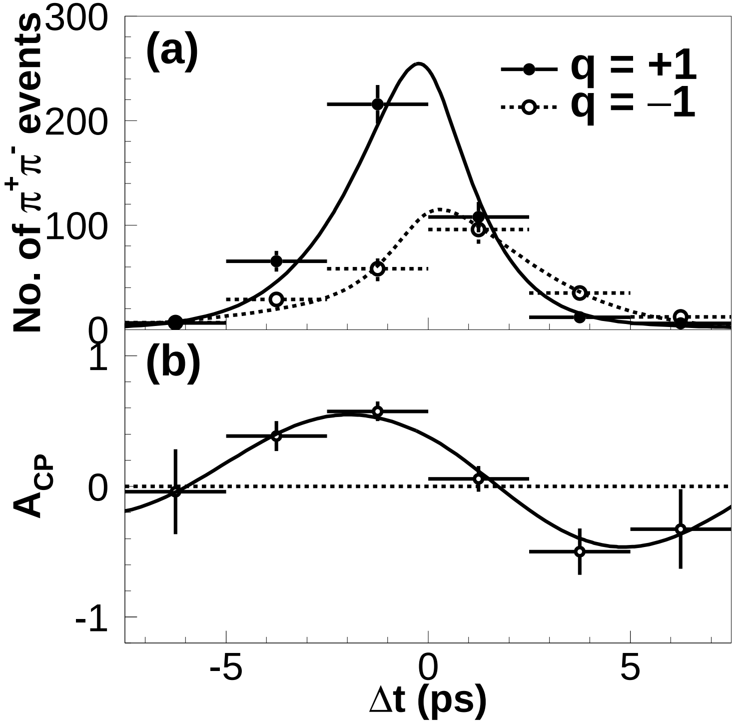
Clear mixing-induced asymmetry

Belle

PRL **98**, 211801 (2007)

535 million $B\bar{B}$ pairs

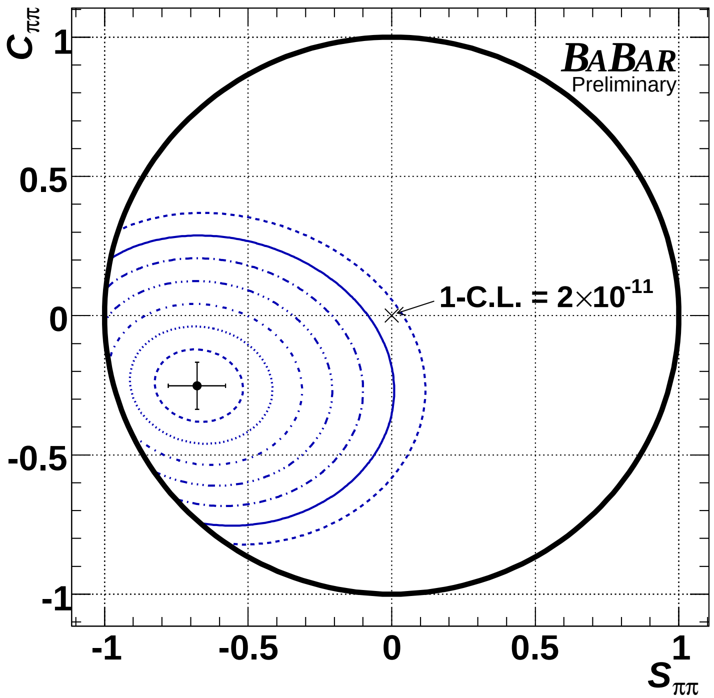
Δt distribution and asymmetry

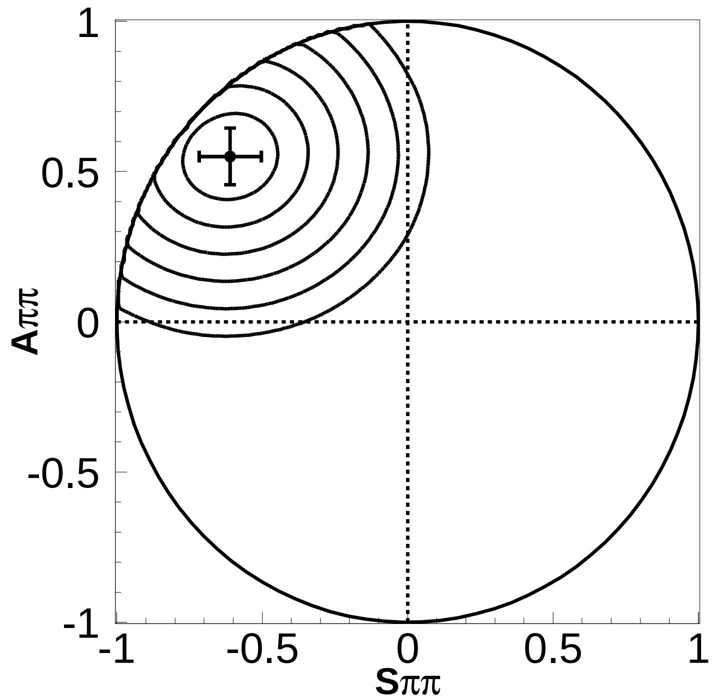


Height difference shows direct CP asymmetry

$B \longrightarrow \pi\pi$

BaBar	Belle
$\mathcal{A}_{CP} = +0.25 \pm 0.08 \pm 0.02 \; (3.0\sigma)$	$\mathcal{A}_{CP} = +0.55 \pm 0.08 \pm 0.05 \; (5.5\sigma)$
$\mathcal{S}_{CP} = -0.68 \pm 0.10 \pm 0.03 \; (6.3\sigma)$	$\mathcal{S}_{CP} = -0.61 \pm 0.10 \pm 0.04 \; (5.3\sigma)$





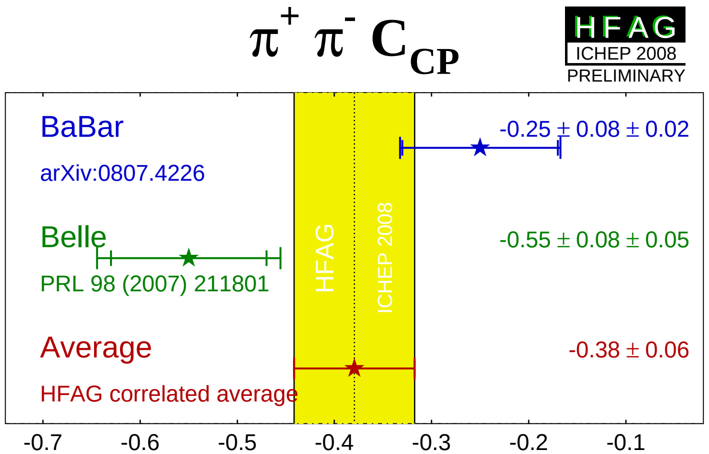
$\mathcal{C}_{CP} = -\mathcal{A}_{CP}$

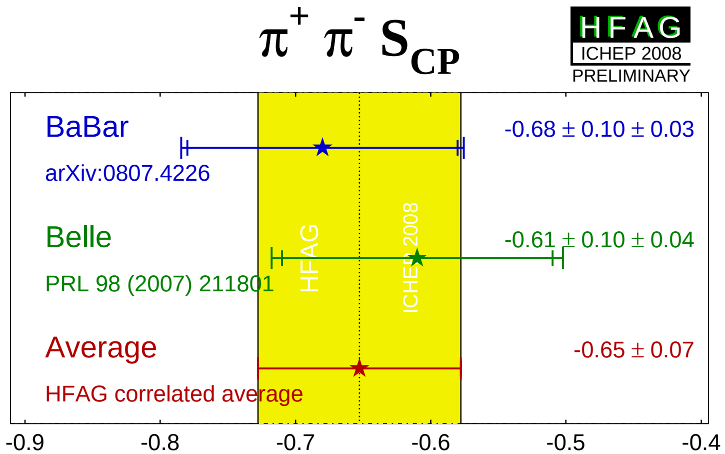
CP violation observed in individual parameters

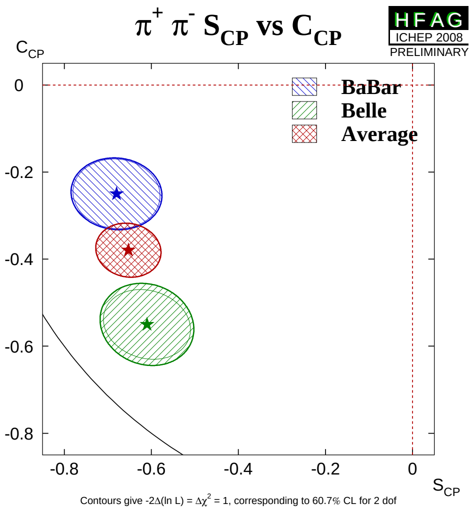
Both experiments have observed CP violation

$B \to \pi\pi$

World average







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

Difference between BaBar and Belle measurements down to 1.9σ

Both experiments demonstrate that more than a tree amplitude is present

$B \longrightarrow \pi\pi$

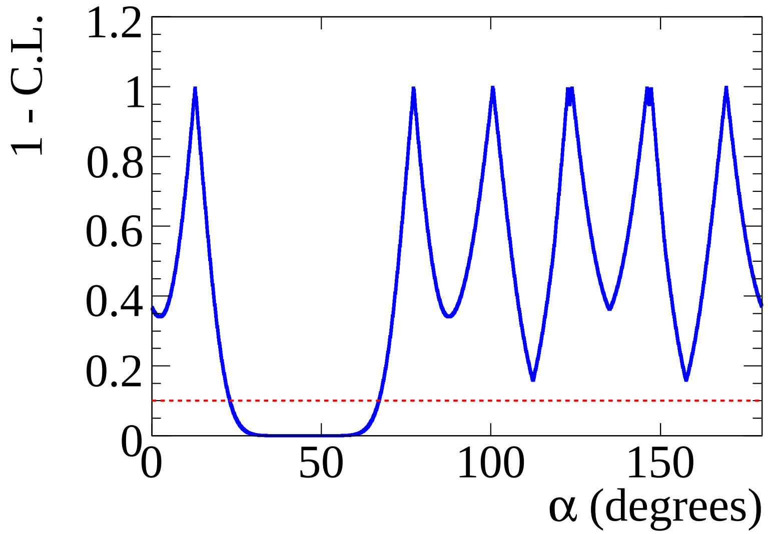
Construct χ^2 for 6 physical observables from 5 constraining isospin amplitudes and ϕ_2

$$(A_{+0}, A_{+-}, A_{00}, \bar{A}_{+-}, \bar{A}_{00})$$

Scan ϕ_2, minimise χ^2 and convert to CL for $6 - 5 = 1$ degree of freedom

BaBar

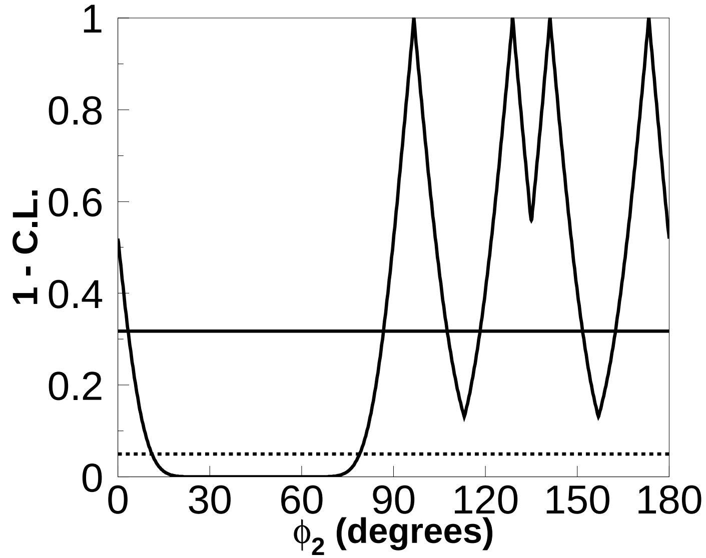
Use BaBar results only



$[23°, 67°]$ excluded at 90% CL

Belle

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



$[11°, 79°]$ excluded at 95% CL

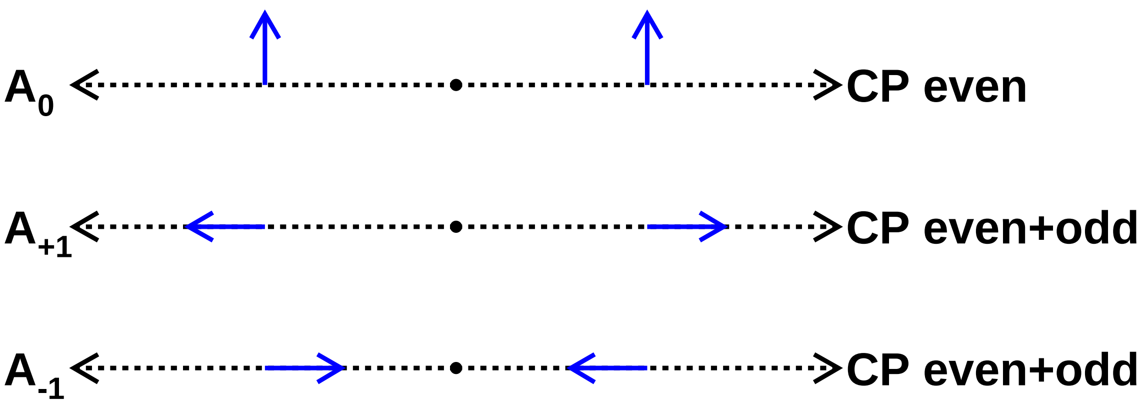
$B \to \rho\rho$

$S \to VV$, Spin $0 \to 1+1$

$J_{\rho\rho} = 0$ and orbital angular momentum, L, has no component along the decay axis

Final state a superposition of 3 possible polarisation amplitudes: 1 longitudinal and 2 transverse

In the helicity basis,

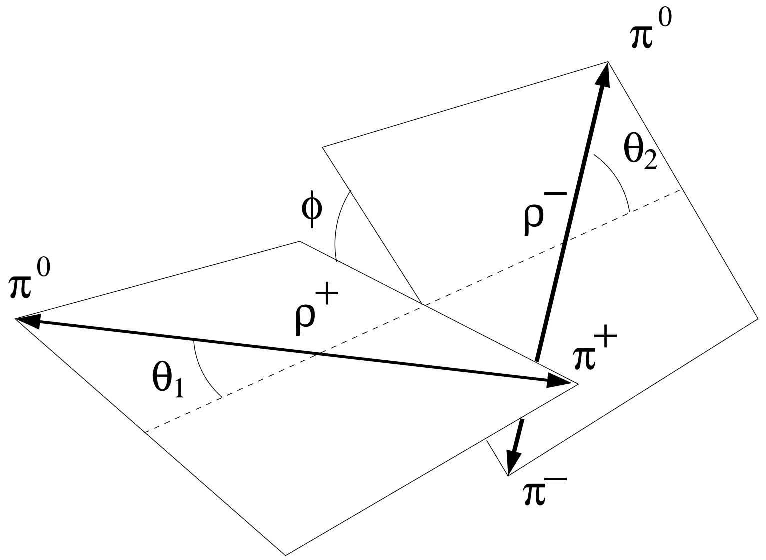


$CP = (-1)^L$

$L = 0, 2 \to CP = +1$

$L = 0, 1, 2 \to CP =$ mixed

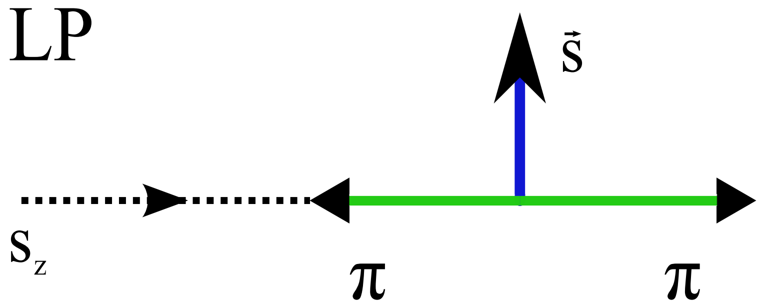
$B \to \rho\rho$

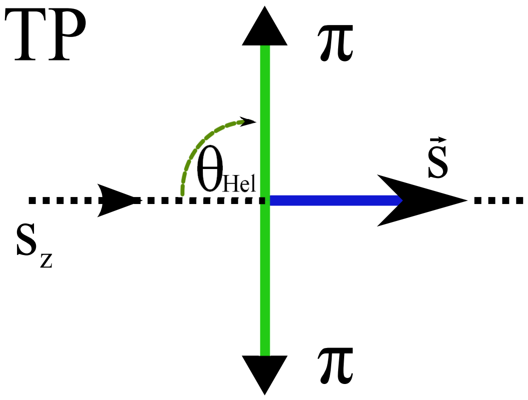


Decompose the longitudinal contribution

Integrating over ϕ, angular decay rate

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





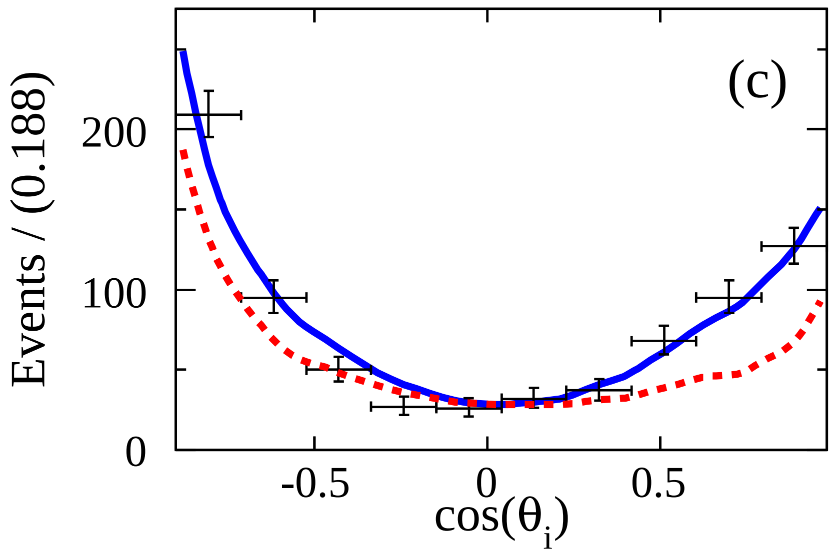
$B^+ \to \rho^+ \rho^-$

BaBar

PRD **76** 052007 (2007)

384 million $B\bar{B}$ pairs

Helicity



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

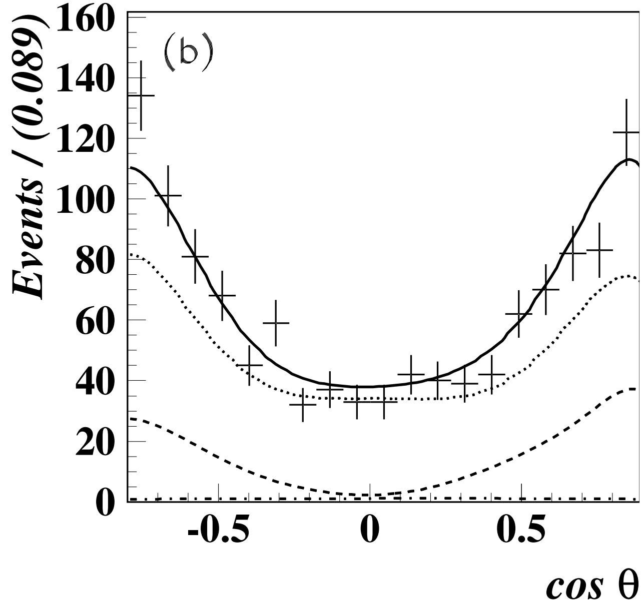
$$f_L = 0.992 \pm 0.024 \text{ (stat)}^{+0.026}_{-0.013} \text{ (syst)}$$

Belle

PRL **96** 171801 (2006)

275 million $B\bar{B}$ pairs

Helicity



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

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

Longitudinal polarisation dominates

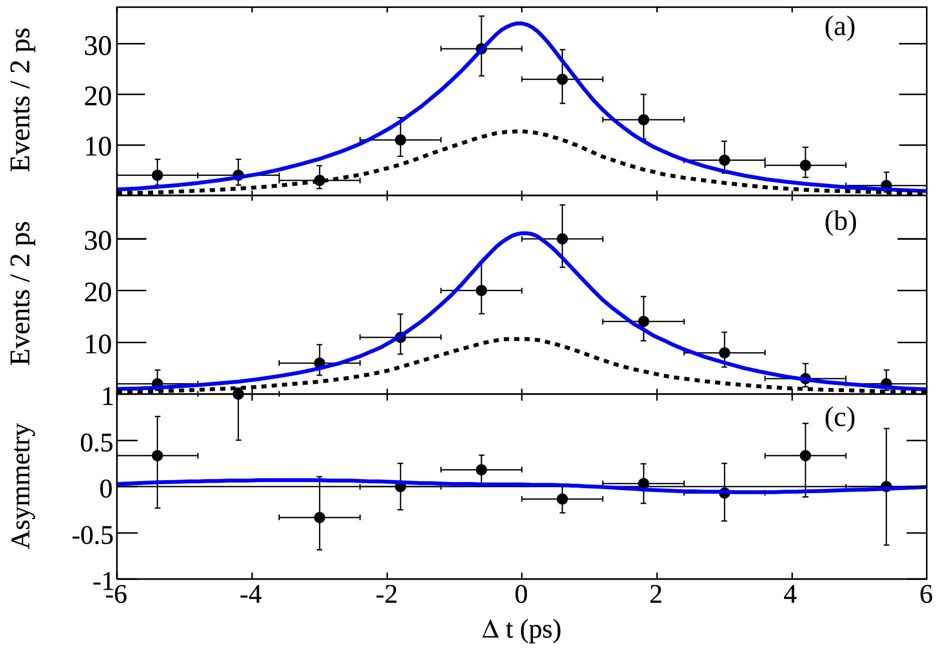
$B^+ \to \rho^+ \rho^-$

BaBar

PRD **76** 052007 (2007)

384 million $B\bar{B}$ pairs

Δt distribution and asymmetry



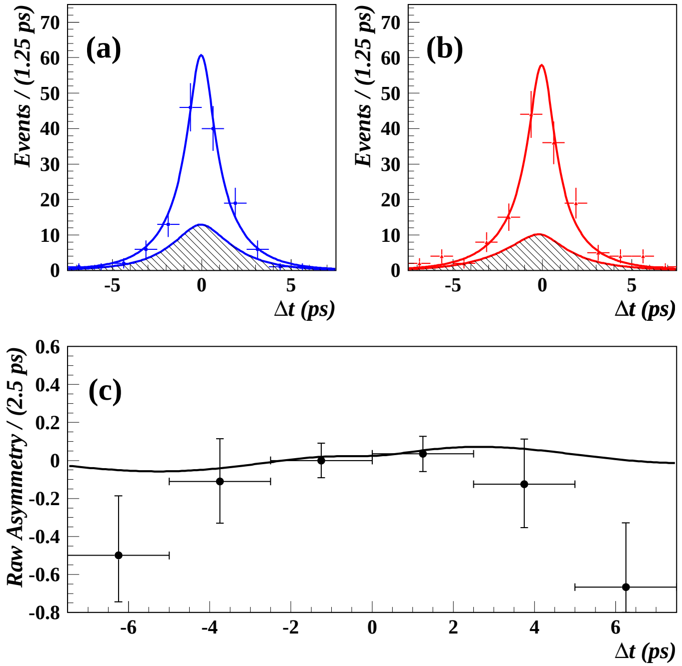
$$\mathcal{A}_{CP} = -0.01 \pm 0.15 \pm 0.06$$
$$\mathcal{S}_{CP} = -0.17 \pm 0.20^{+0.05}_{-0.06}$$

Belle

PRD **76** 011104 (2007)

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

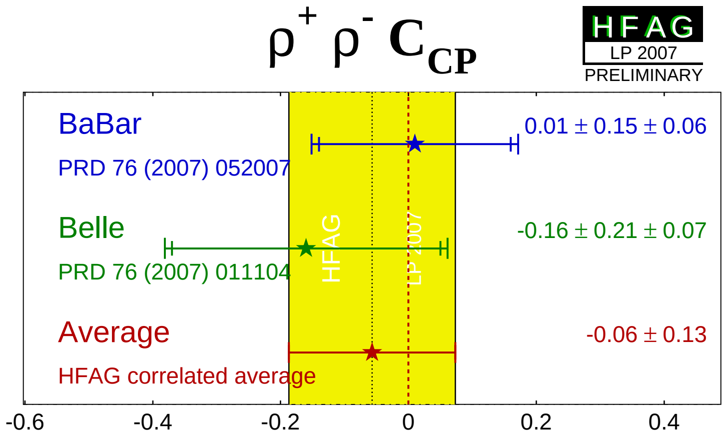
Δt distribution and asymmetry

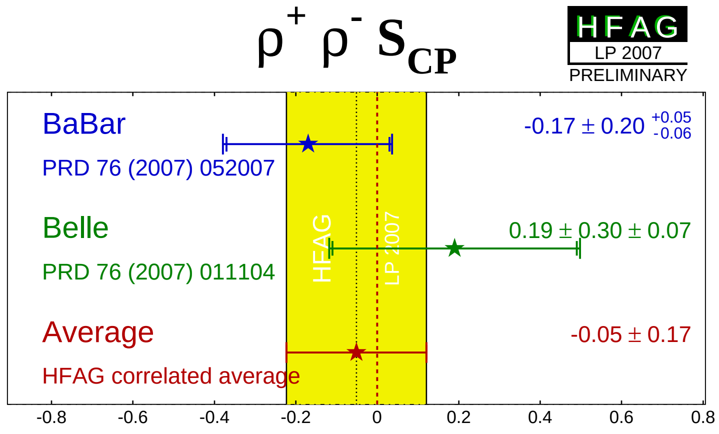


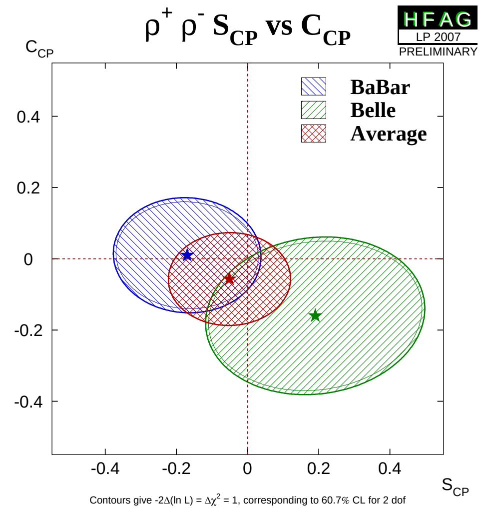
$$\mathcal{A}_{CP} = +0.16 \pm 0.21 \pm 0.07$$
$$\mathcal{S}_{CP} = +0.19 \pm 0.30 \pm 0.07$$

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

World average







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

Good agreements between experiments

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

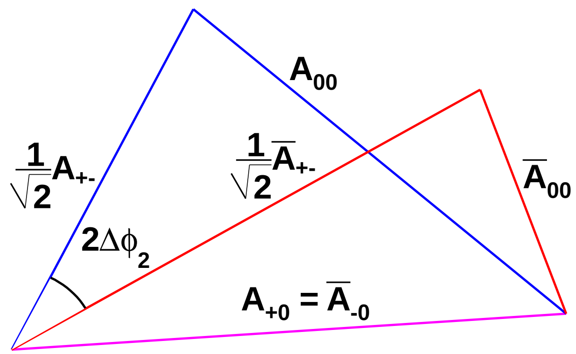
$B^+ \to \rho^+\rho^0$

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



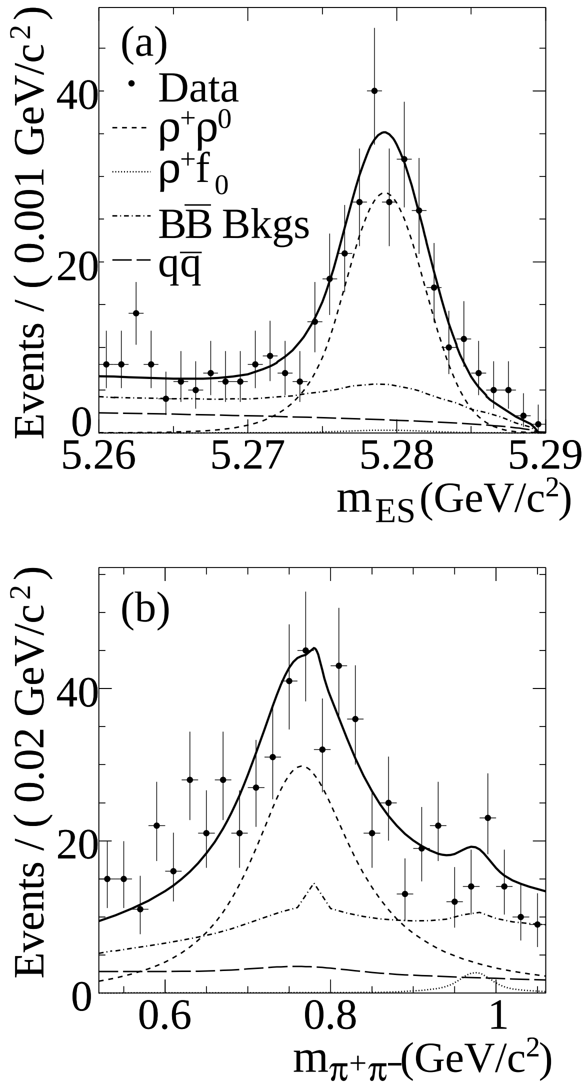
$$f_L = 0.950 \pm 0.015 \pm 0.006$$

Dominantly longitudinally polarised

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

No evidence for electroweak penguins

Belle will update this analysis soon with $\sim$10 times statistics



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

Time-dependent measurement removes 4-fold ambiguity of $\Delta\phi_2$

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

BaBar

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

465 million $B\bar{B}$ pairs

$N(B^0 \to \rho^0\rho^0) = 99^{+35}_{-34} \pm 15$

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

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

3.1σ evidence

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

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

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

Belle

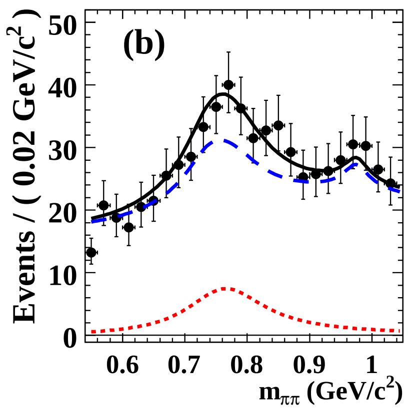
PRD **78** 111102(R) (2008)

657 million $B\bar{B}$ pairs

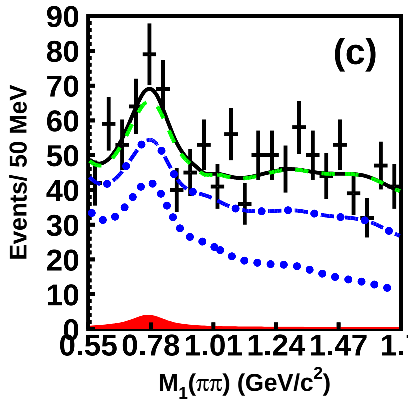
$N(B^0 \to \rho^0\rho^0) = 24.5^{+23.6+10.1}_{-22.1-16.2}$

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

BaBar



Belle



$B^0 \to \rho\rho$

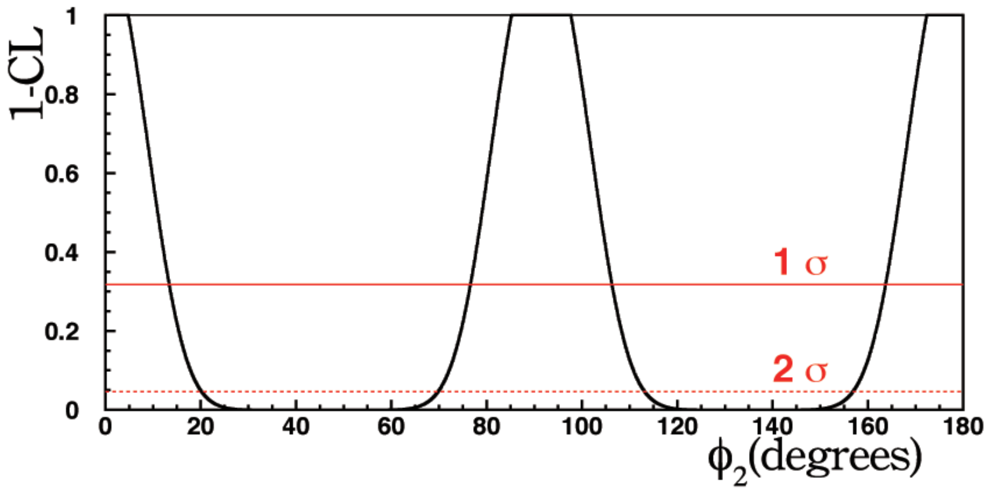
Branching fraction of $B^+ \to \rho^+\rho^0$ large compared to $B^0 \to \rho^0\rho^0$

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

Belle

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

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



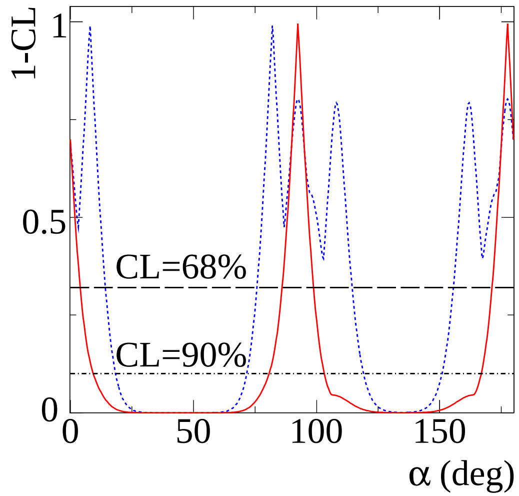
Plateau due to no constraint on $\mathcal{A}_{CP}(\rho^0\rho^0)$

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

BaBar

PRL **102** 141802 (2009)

Use BaBar results only



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

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

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

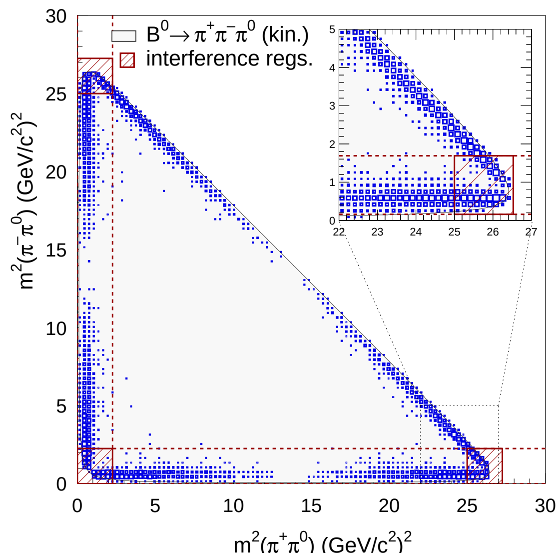
$B^0 \to (\rho\pi)^0$

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



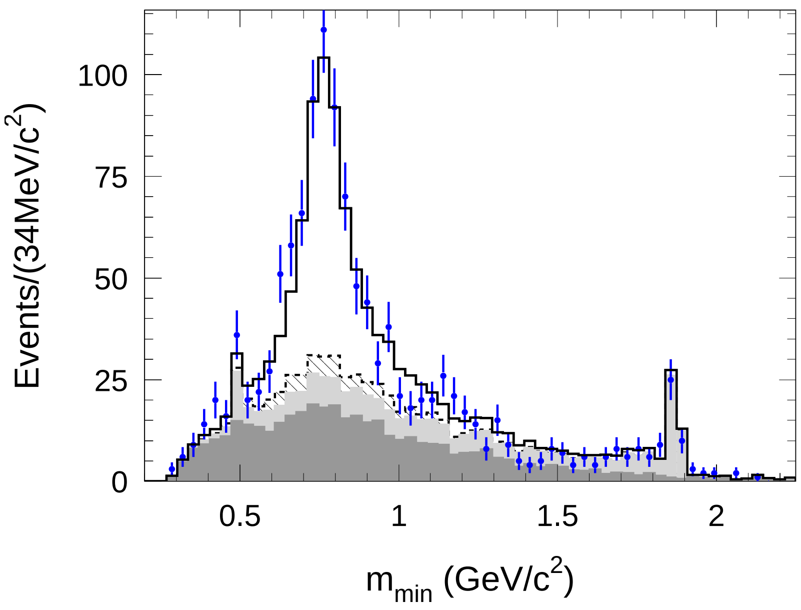
$B^0 \to (\rho\pi)^0$

BaBar

PRD **76** 012004 (2007)

375 million $B\bar{B}$ pairs

Mass projections



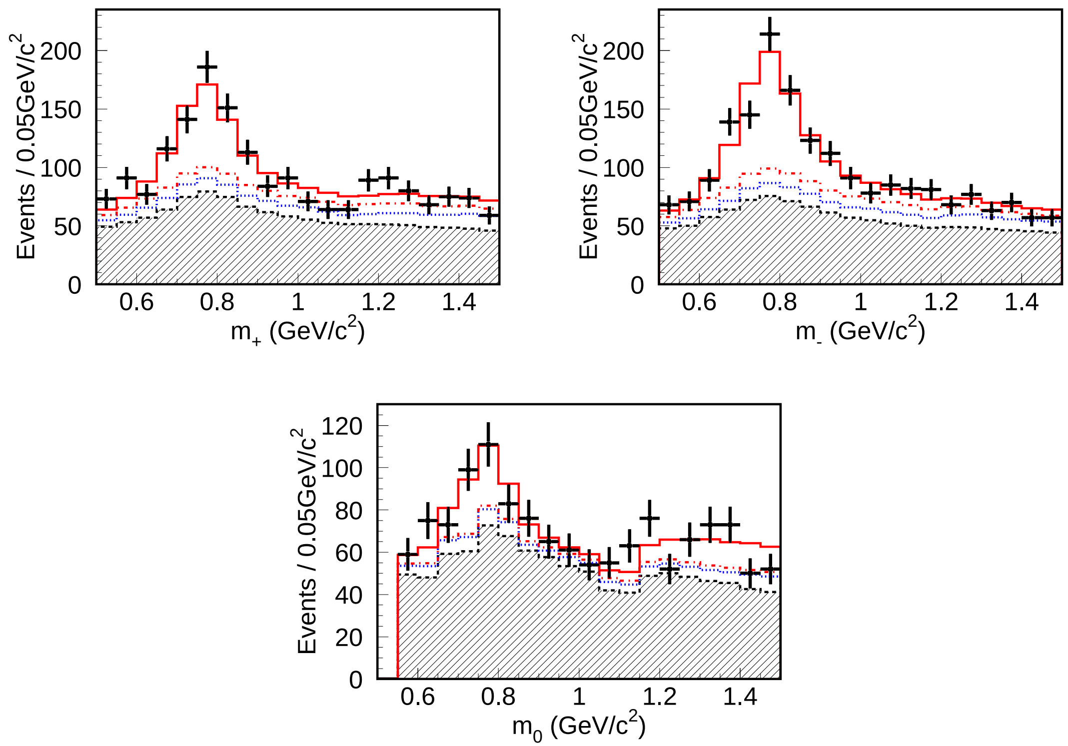
Plot minimum of m_+, m_-, m_0

Belle

PRL **98** 221602 (2007)

449 million $B\bar{B}$ pairs

Mass projections

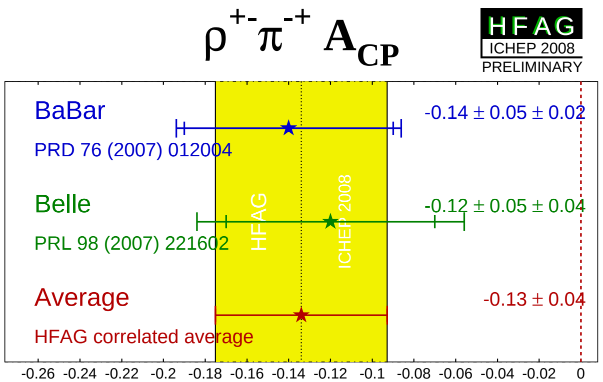


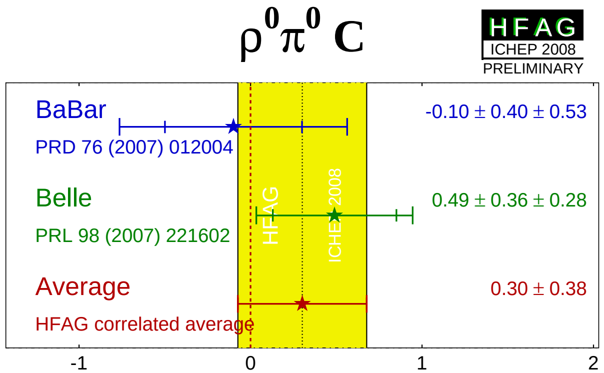
$B^0 \to (\rho\pi)^0$

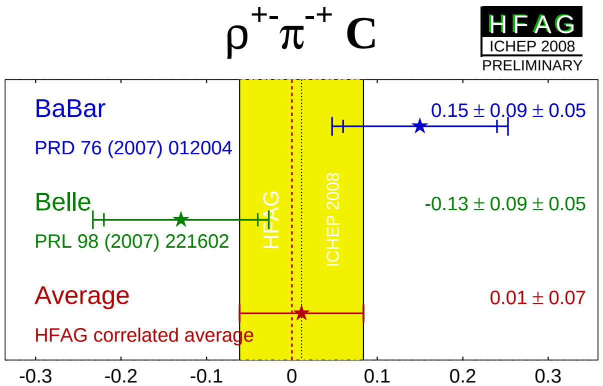
For $B^0 \to \rho^\pm \pi^\mp$

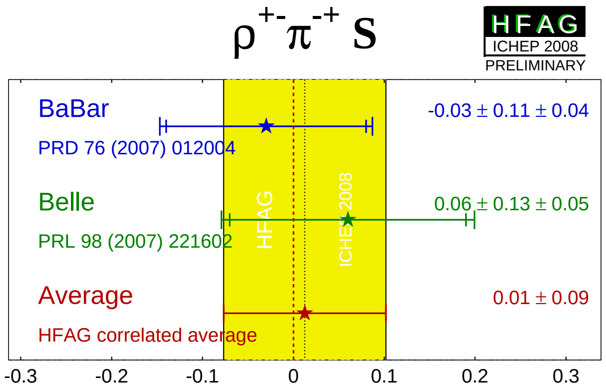
For $B^0 \to \rho^0 \pi^0$

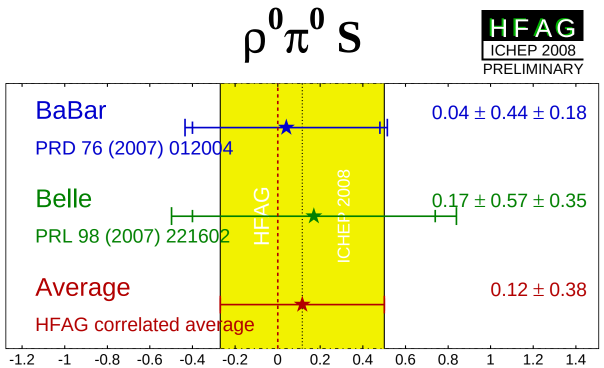
$\mathcal{A}_{CP}$ is time and flavour-integrated CP asymmetry











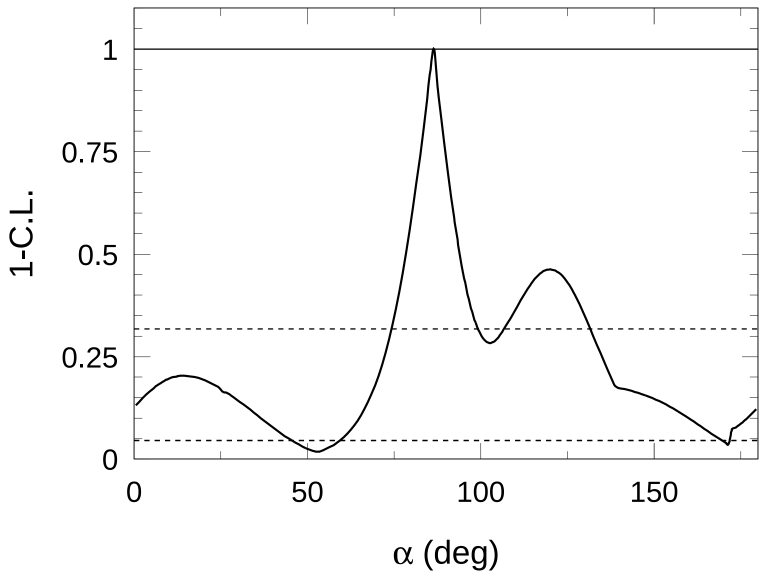
Good agreement between experiments

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

Perform ϕ_2 scan

BaBar

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

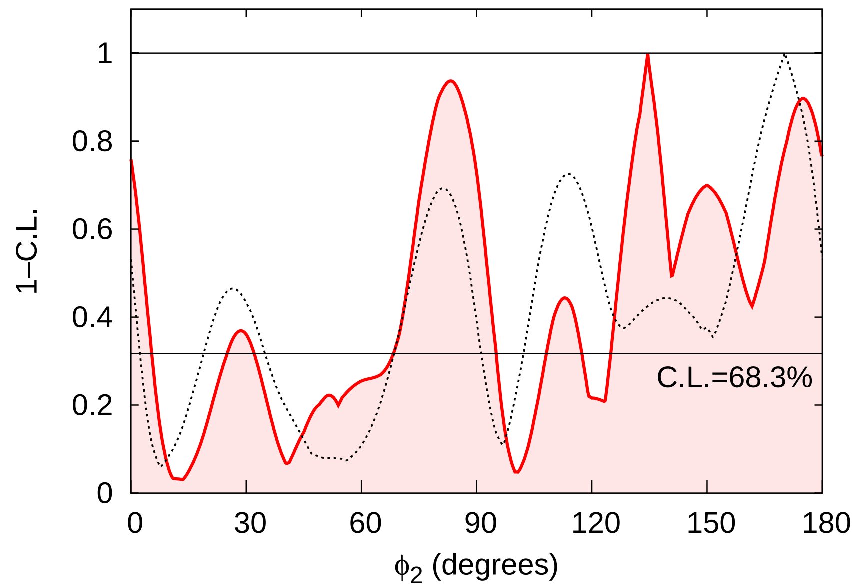


$\phi_2 = (87^{+45}_{-13})^\circ$

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

Summary

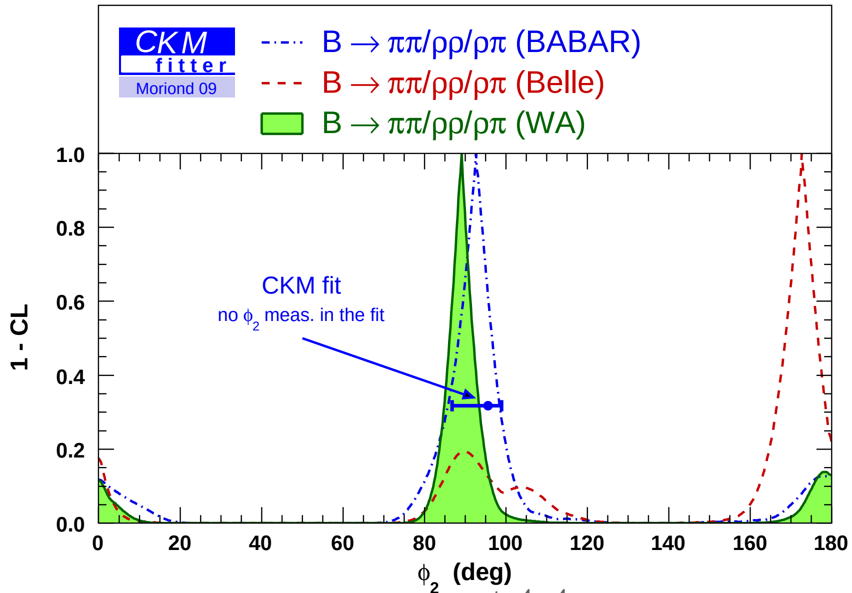
Many measurements of ϕ_2 performed by the B factories

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

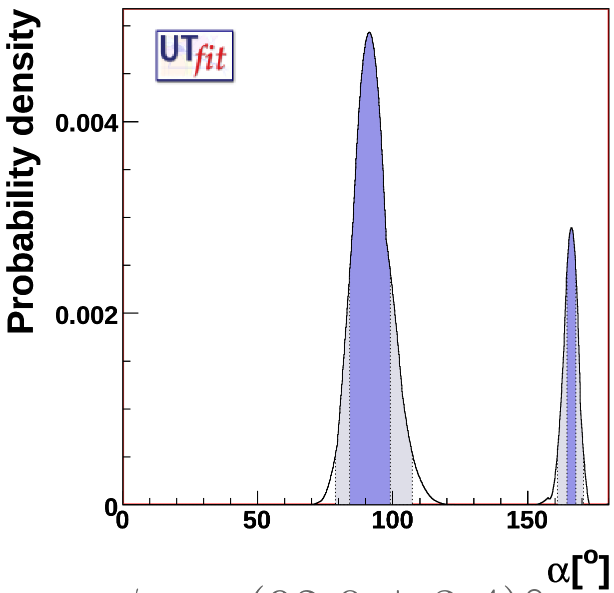
But only $B^0 \to (\rho\pi)^0$ can ultimately constrain ϕ_2 without ambiguity

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

Many final results from the B factories still anticipated



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



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

Backup

$B \to \pi\pi$ Observables

BaBar

467 million $B\bar{B}$ pairs

$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$

$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = +0.43 \pm 0.26 \pm 0.05$

arXiv:0807.4226 (2008)

383 million $B\bar{B}$ pairs

$\mathcal{B}(B^+ \to \pi^+\pi^0) = (5.02 \pm 0.46 \pm 0.29) \times 10^{-6}$

$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = +0.03 \pm 0.08 \pm 0.01$

PRD 76 091102 (2007)

Belle

535 million $B\bar{B}$ pairs

$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.1 \pm 0.3 \pm 0.1) \times 10^{-6}$

$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = +0.44^{+0.73}_{-0.62}{}^{+0.04}_{-0.06}$

arXiv:hep-ex/0610065 (2006)

449 million $B\bar{B}$ pairs

$\mathcal{B}(B^+ \to \pi^+\pi^0) = (6.5 \pm 0.4^{+0.4}_{-0.5}) \times 10^{-6}$

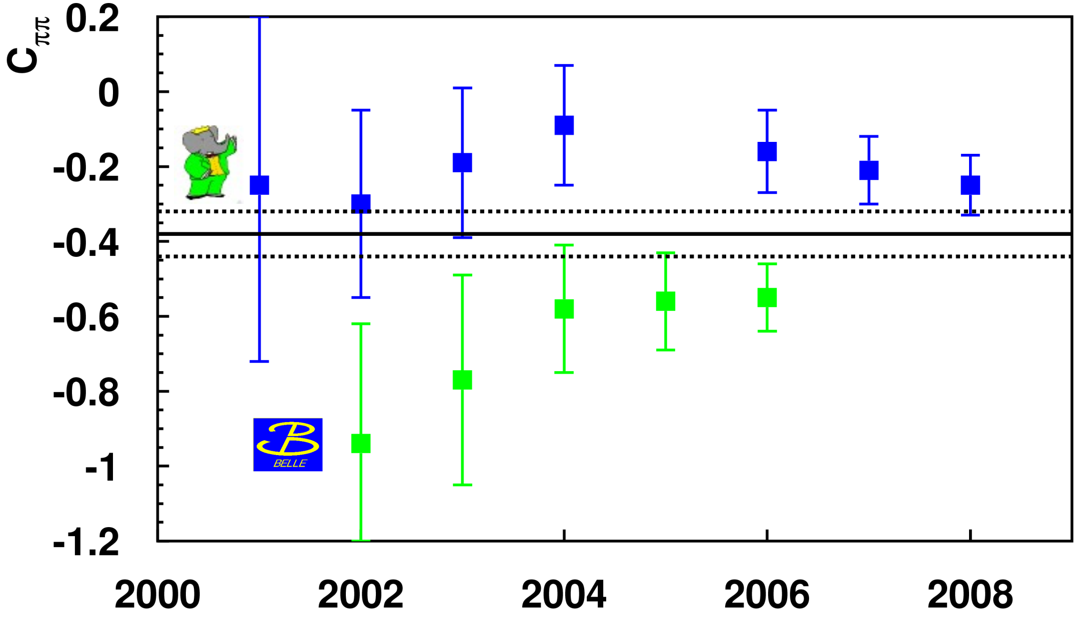
PRL 99 121601 (2007)

535 million $B\bar{B}$ pairs

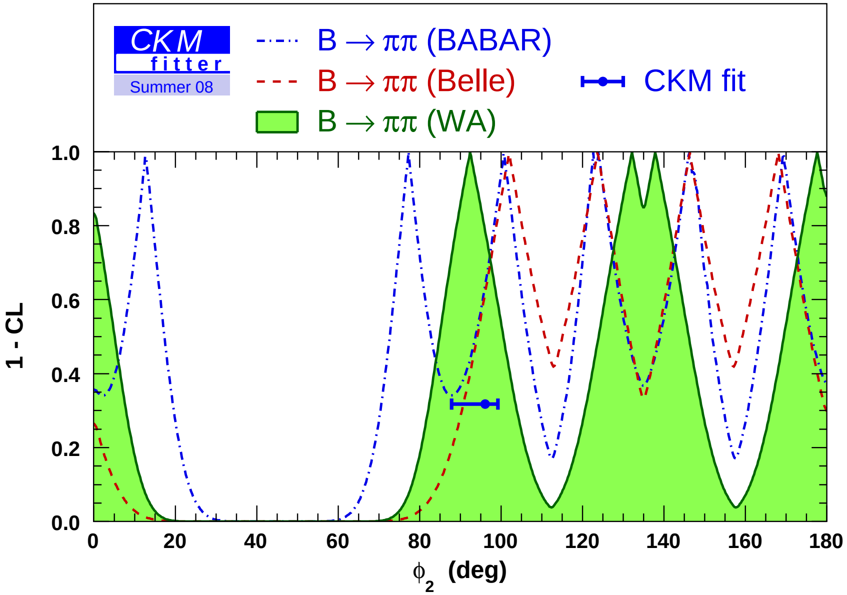
$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = +0.07 \pm 0.06 \pm 0.01$

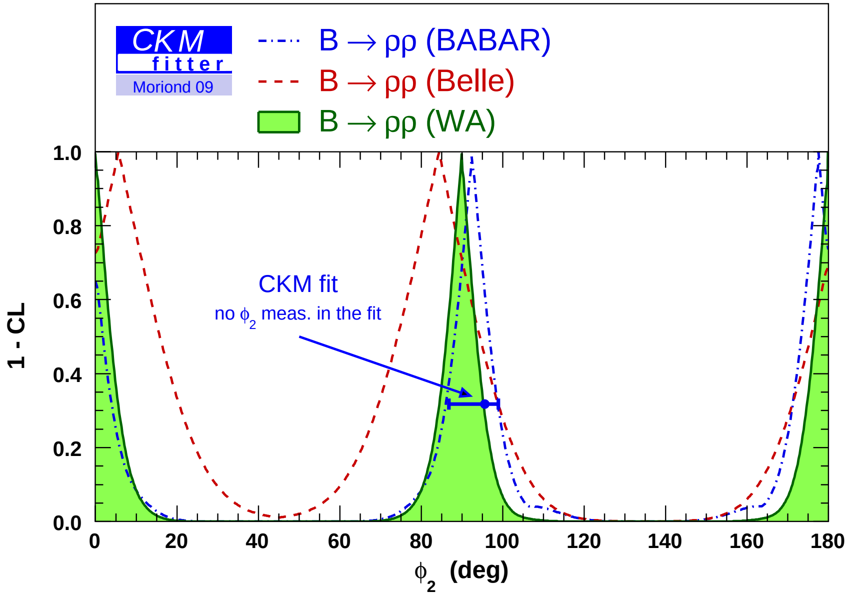
Nature 452 332 (2008)

History of $B \longrightarrow \pi\pi$

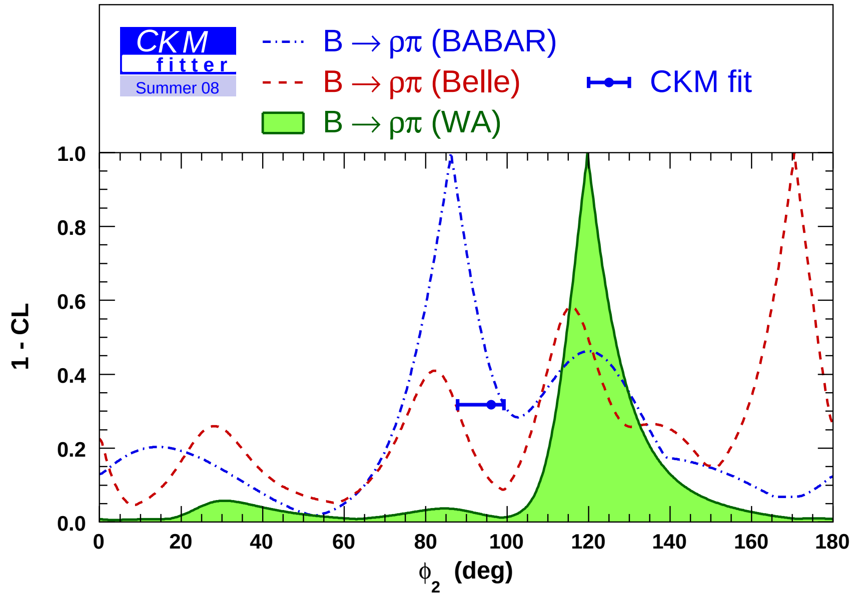


ϕ_2 Averages





ϕ_2 Averages



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

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

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

$$U_\kappa^\pm = |A_\kappa|^2 \pm |\bar{A}_\kappa|^2$$
$$U_{\kappa\sigma}^{\pm,\Re} = \Re[A_\kappa A_\sigma^* \pm \bar{A}_\kappa \bar{A}_\sigma^*]$$
$$U_{\kappa\sigma}^{\pm,\Im} = \Im[A_\kappa A_\sigma^* \pm \bar{A}_\kappa \bar{A}_\sigma^*]$$
$$I_\kappa = \Im[\bar{A}_\kappa A_\kappa^*]$$
$$I_{\kappa\sigma}^{\Re} = \Re[\bar{A}_\kappa A_\sigma^* - \bar{A}_\sigma A_\kappa^*]$$
$$I_{\kappa\sigma}^{\Im} = \Im[\bar{A}_\kappa A_\sigma^* + \bar{A}_\sigma A_\kappa^*]$$

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

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

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