

Studies Related to the CKM angles ϕ_2 and ϕ_3 at Belle

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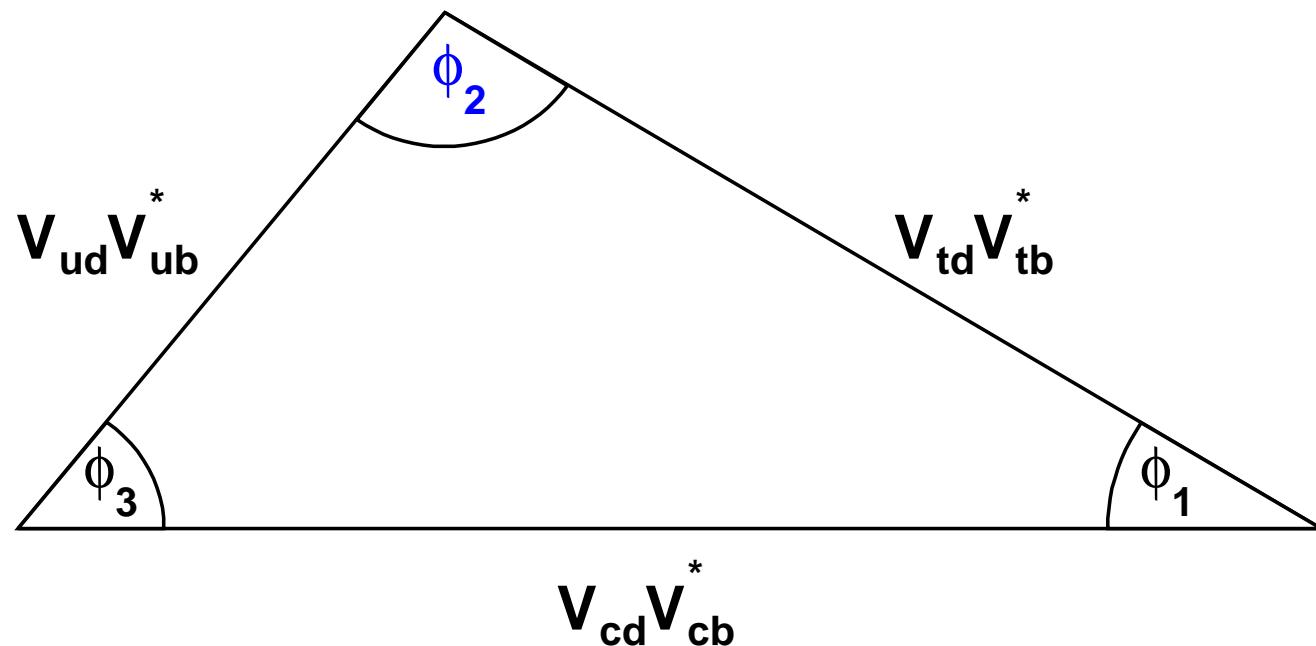
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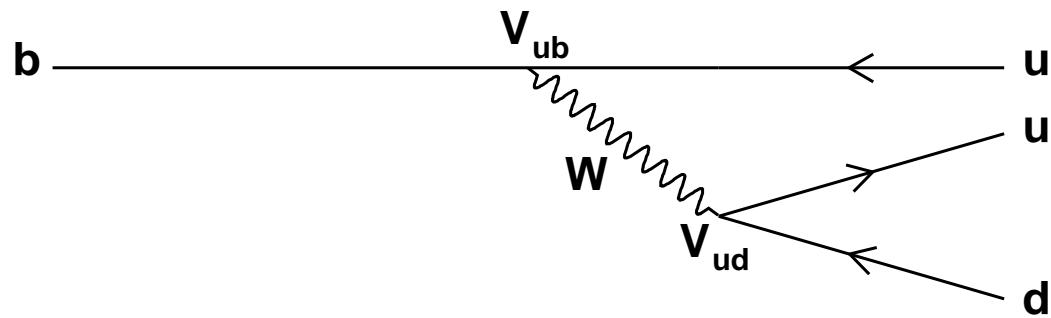
Outline

1. $B^0 \rightarrow a_1(1260)^\pm \pi^\mp$
2. ϕ_3 with GLW, ADS, GGSZ

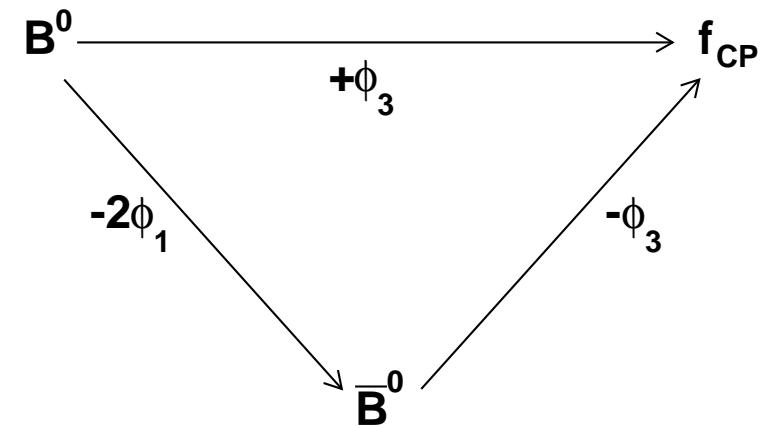


Introduction

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



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



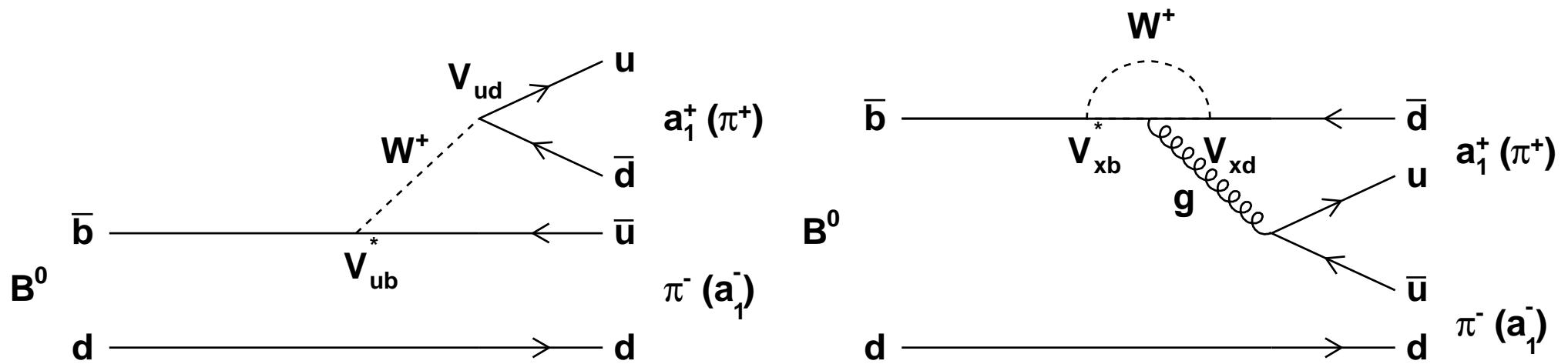
Measure a time difference between B decays, Δt , and the flavour of the tag-side B , q

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

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

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

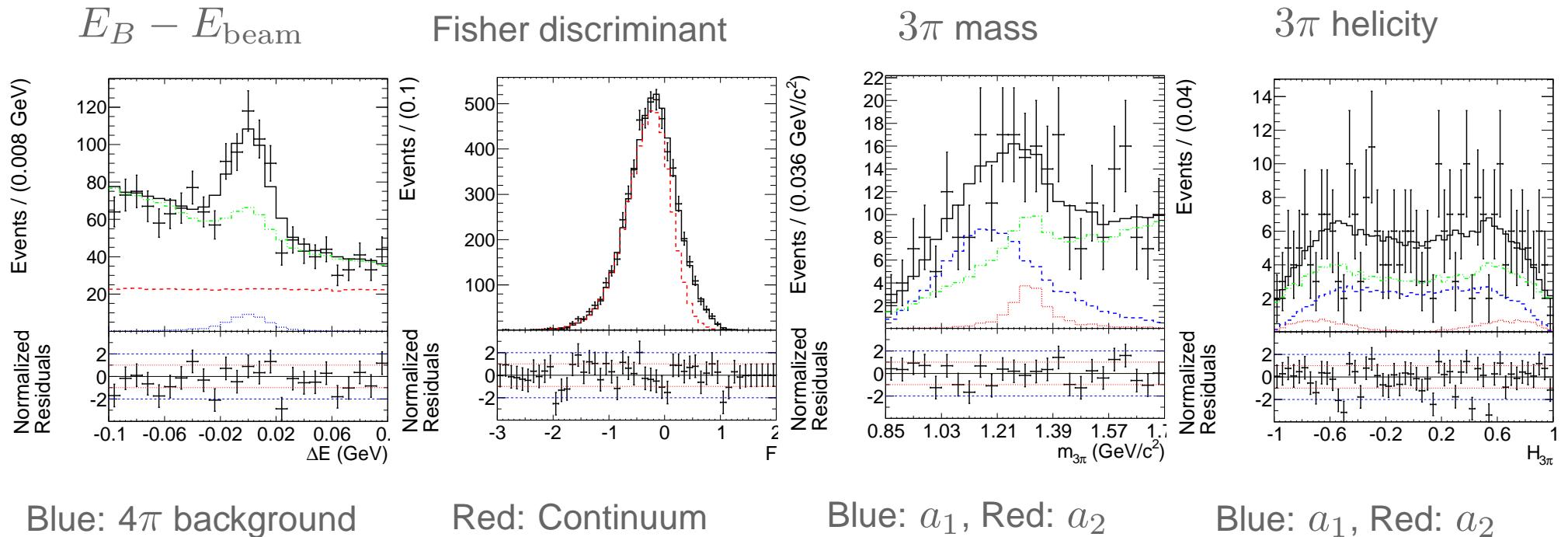
$$B^0 \rightarrow a_1(1260)^\pm \pi^\mp$$

arXiv:1205.5957

Reconstructed in 4 charged pion final state

Difficulties from huge continuum background and other 4 pion backgrounds

Extract branching fraction from 4 discriminating variables



$$\mathcal{B}(B^0 \rightarrow a_1(1260)^\pm \pi^\mp) \times \mathcal{B}(a_1^\pm(1260) \rightarrow \pi^\pm \pi^\mp \pi^\pm) = (11.1 \pm 1.0 \text{ (stat)} \pm 1.4 \text{ (syst)}) \times 10^{-6}$$

$$B^0 \rightarrow a_1(1260)^\pm \pi^\mp$$

Flavour non-specific final state, need to consider 4 flavour-charge configurations (q, c)

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

\mathcal{A}_{CP} : Time and flavour-integrated direct CP violation

\mathcal{C}_{CP} : Flavour-dependent direct CP violation

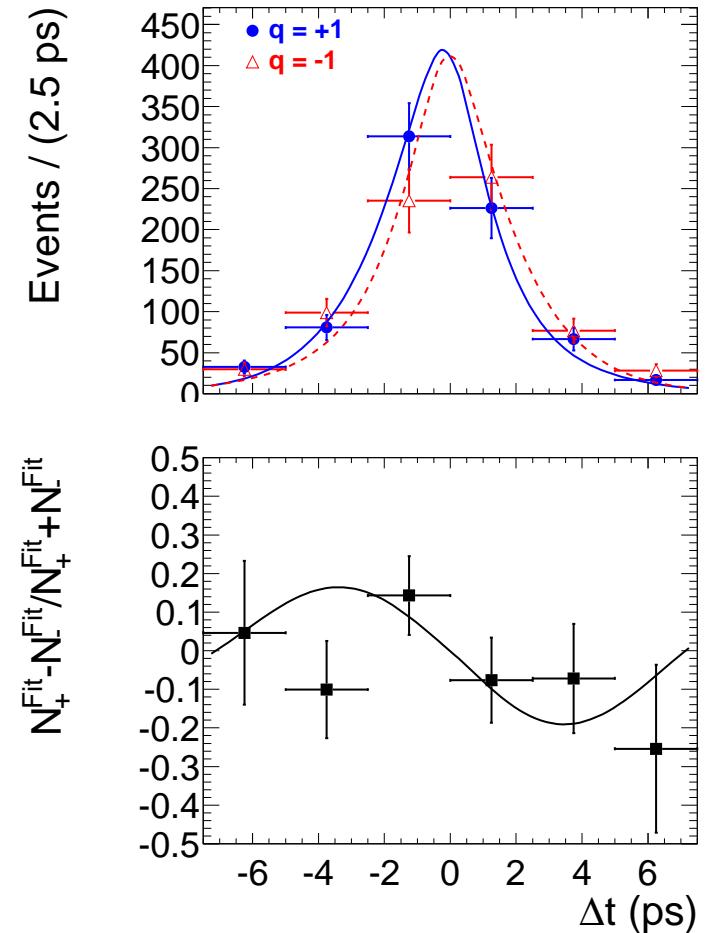
\mathcal{S}_{CP} : Mixing-induced CP violation

$\Delta\mathcal{C}$: Rate asymmetry between configurations where a_1 does not and does contain the spectator quark

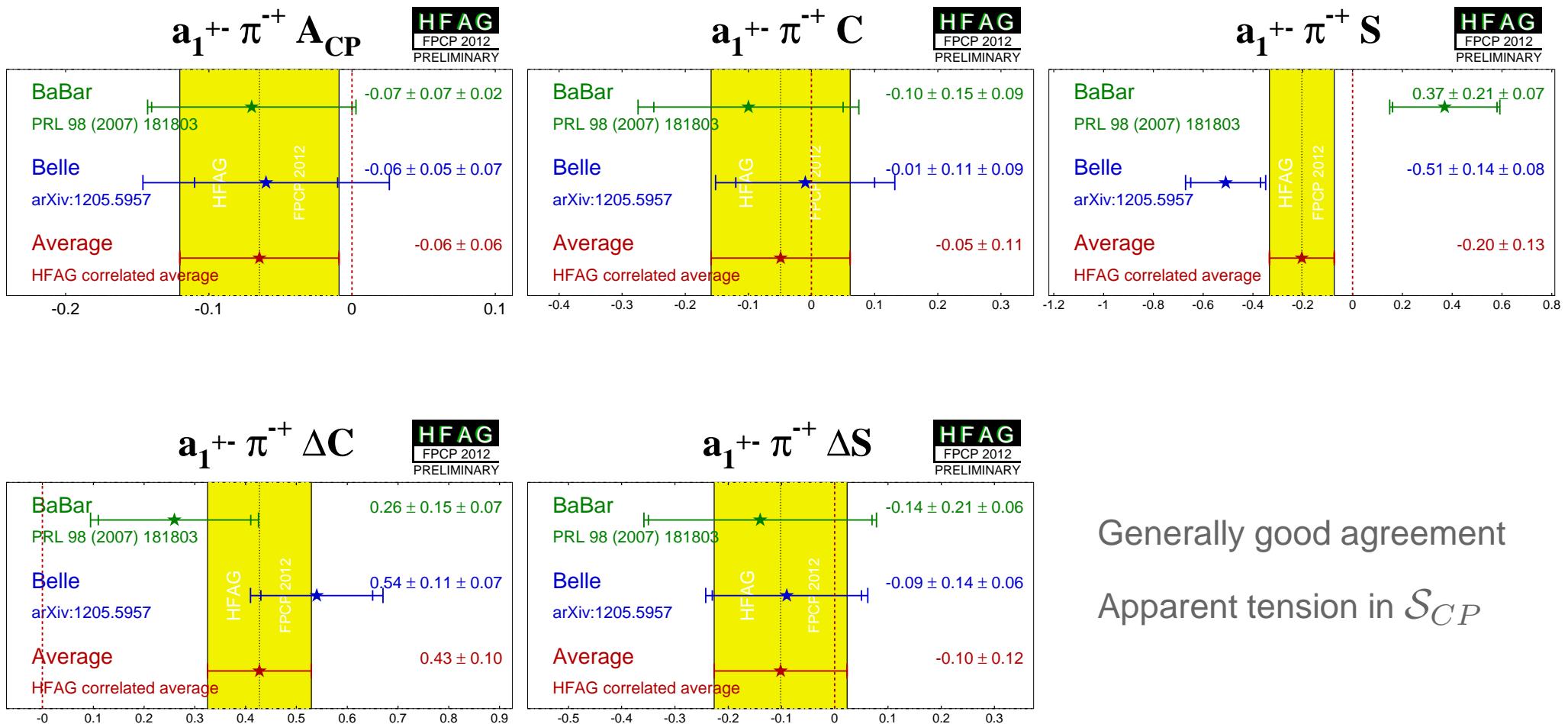
$\Delta\mathcal{S}$: Strong phase difference between configurations where a_1 does not and does contain the spectator quark

$$\mathcal{S}_{CP} = -0.51 \pm 0.14 \text{ (stat)} \pm 0.08 \text{ (syst)}$$

3.1σ evidence for mixing-induced CP violation



$$B^0 \rightarrow a_1(1260)^\pm \pi^\mp$$

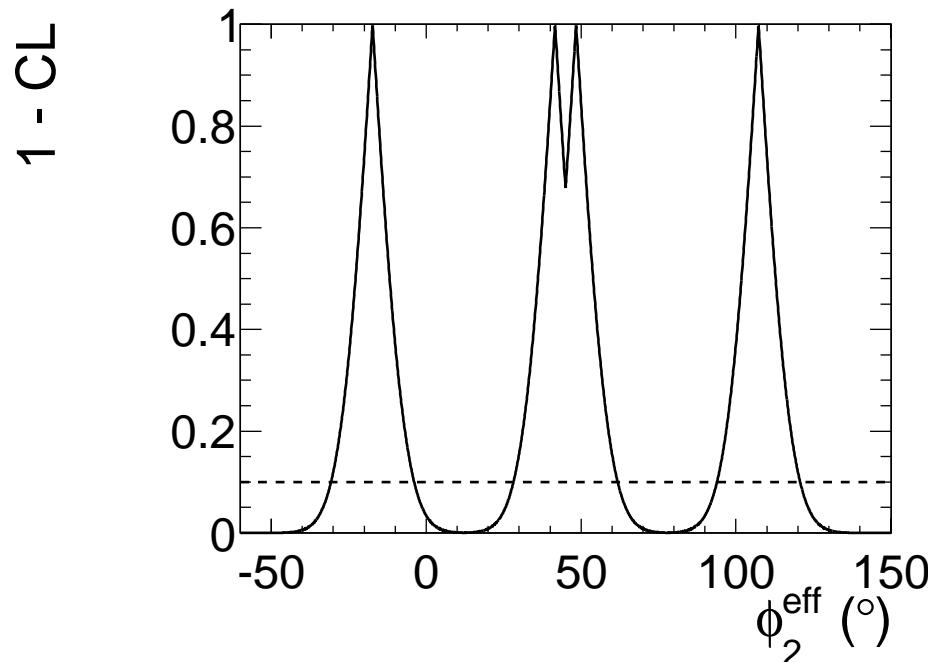


Generally good agreement

Apparent tension in \mathcal{S}_{CP}

$$B^0 \rightarrow a_1(1260)^\pm \pi^\mp$$

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



Recover ϕ_2 with isospin pentagon analysis

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

Or estimate bounds on $|\Delta\phi_2|$ with SU(3) flavour symmetry

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

4 solutions for ϕ_2^{eff}

At 1σ level,

$$\phi_2^{\text{eff}} = [-25.5^\circ, -9.1^\circ]$$

$$= [34.7^\circ, 55.3^\circ]$$

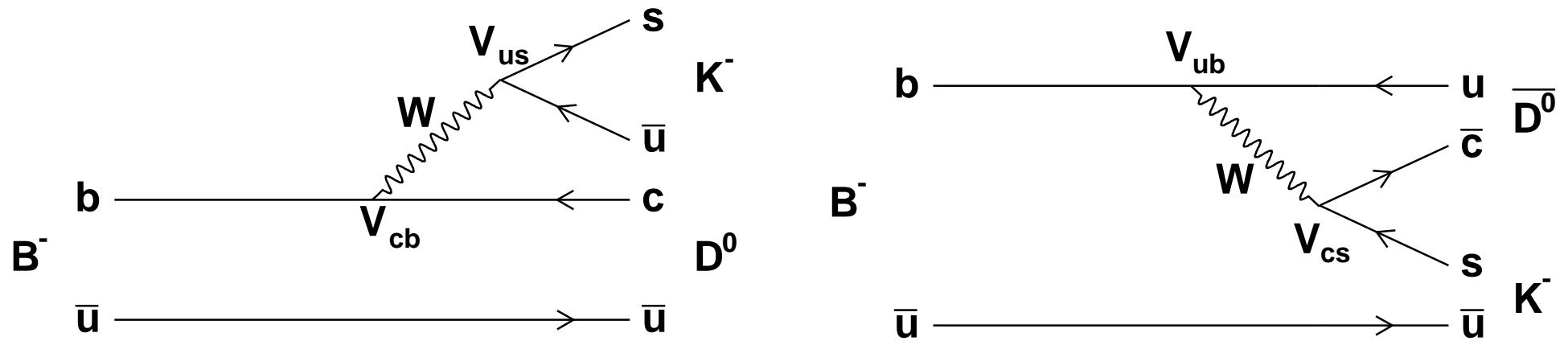
$$= [99.1^\circ, 115.5^\circ]$$

ϕ_3 from B decays

Interference between the dominant $b \rightarrow c\bar{u}s$ with the corresponding DCS $b \rightarrow u\bar{c}s$

$$A \propto \lambda^3$$

$$A \propto \lambda^3(\rho - i\eta)$$



Amplitudes same order in λ but $A(b \rightarrow u\bar{c}s)$ receives $1/3$ from colour suppression

When $D \equiv D^0$ or \bar{D}^0 decays to the same final state, $|D\rangle = |D^0\rangle + r_B e^{i\theta} |\bar{D}^0\rangle$

Amplitude ratio, $r_B = A(B^- \rightarrow \bar{D}^0 K^-)/A(B^- \rightarrow D^0 K^-)$

Phase difference, $\theta = \delta_B \pm \phi_3$ for B^\pm

ϕ_3 With GLW

GLW method: $D^{(*)}$ decays to CP -even ($D_{CP+}^{(*)}$) and CP -odd ($D_{CP-}^{(*)}$) eigenstates

Measured observables

$$R_{CP\pm} = \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm} K^-) + \mathcal{B}(B^+ \rightarrow D_{CP\pm} K^+)}{\mathcal{B}(B^- \rightarrow D^0 K^-) + \mathcal{B}(B^+ \rightarrow \bar{D}^0 K^+)}$$

$$A_{CP\pm} = \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm} K^-) - \mathcal{B}(B^+ \rightarrow D_{CP\pm} K^+)}{\mathcal{B}(B^- \rightarrow D_{CP\pm} K^-) + \mathcal{B}(B^+ \rightarrow D_{CP\pm} K^+)}$$

Relationship between observables constrain ϕ_3

CP -even D_{CP+} decays

$$R_{CP+} = 1 + r_B^2 + 2r_B \cos \delta_B \cos \phi_3$$

$$A_{CP+} = \frac{2r_B \sin \delta_B \sin \phi_3}{1 + r_B^2 + 2r_B \cos \delta_B \cos \phi_3}$$

CP -odd D_{CP-} decays

$$R_{CP-} = 1 + r_B^2 - 2r_B \cos \delta_B \cos \phi_3$$

$$A_{CP-} = \frac{-2r_B \sin \delta_B \sin \phi_3}{1 + r_B^2 - 2r_B \cos \delta_B \cos \phi_3}$$

ϕ_3 With GLW

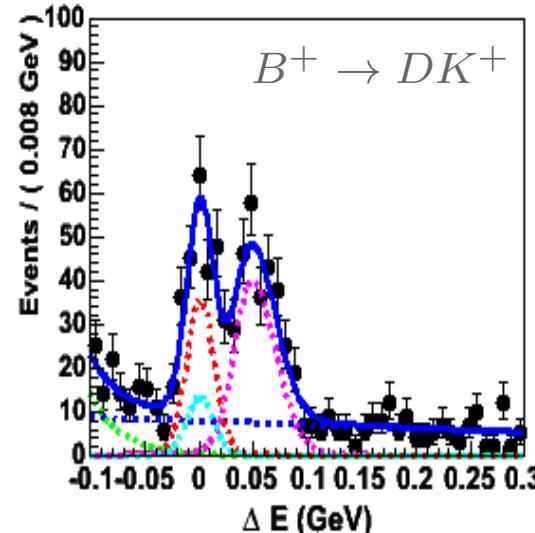
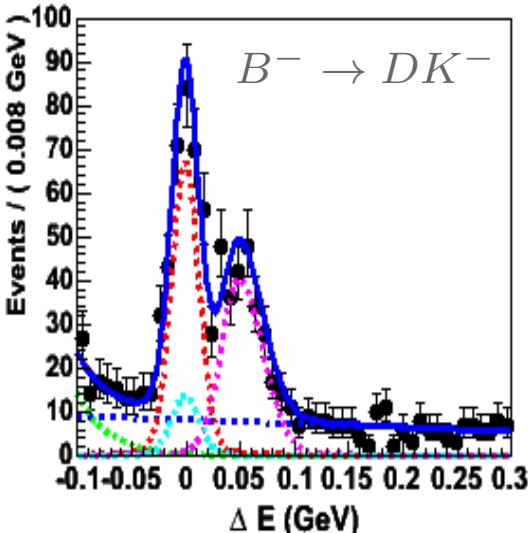
Interference between the dominant $b \rightarrow c\bar{u}s$ with the corresponding DCS $b \rightarrow u\bar{c}s$

Relationship between observables constrain ϕ_3

CP -even D_{CP} decays

Belle: Preliminary

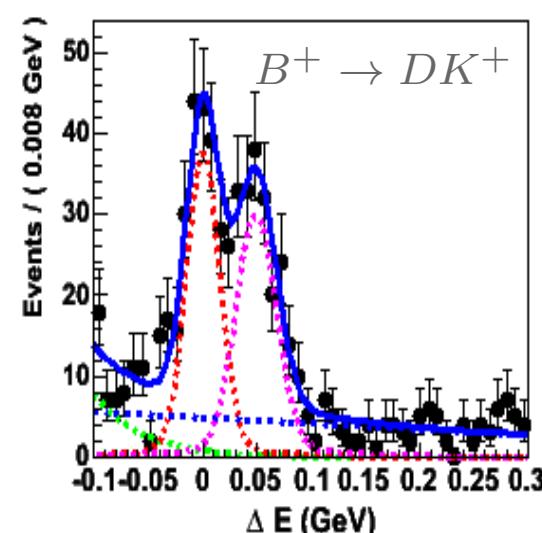
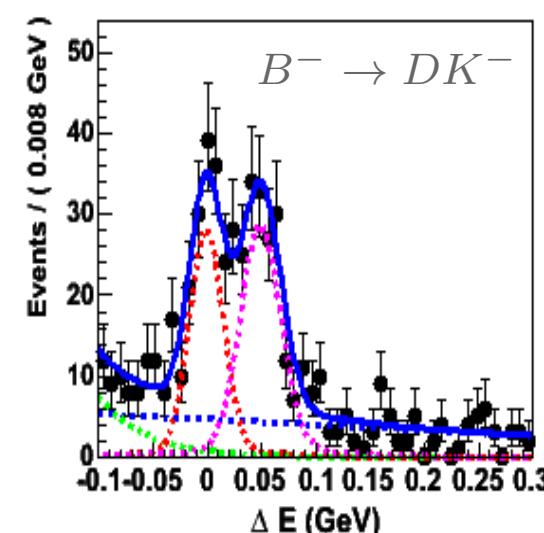
$$D_{CP+} \rightarrow \pi^+\pi^-, K^+K^-$$



CP -odd D_{CP} decays

Belle: Preliminary

$$D_{CP-} \rightarrow K_S^0\pi^0, K_S^0\eta$$



Red: $B \rightarrow DK$, Cyan: Charmless $K^+K^-K^+$

$$R_{CP+} = (7.56 \pm 0.51)\%$$

$$A_{CP+} = (+28.7 \pm 6.0)\%$$

Pink: $B \rightarrow D\pi$, Green: $B\bar{B}$, Blue: Continuum

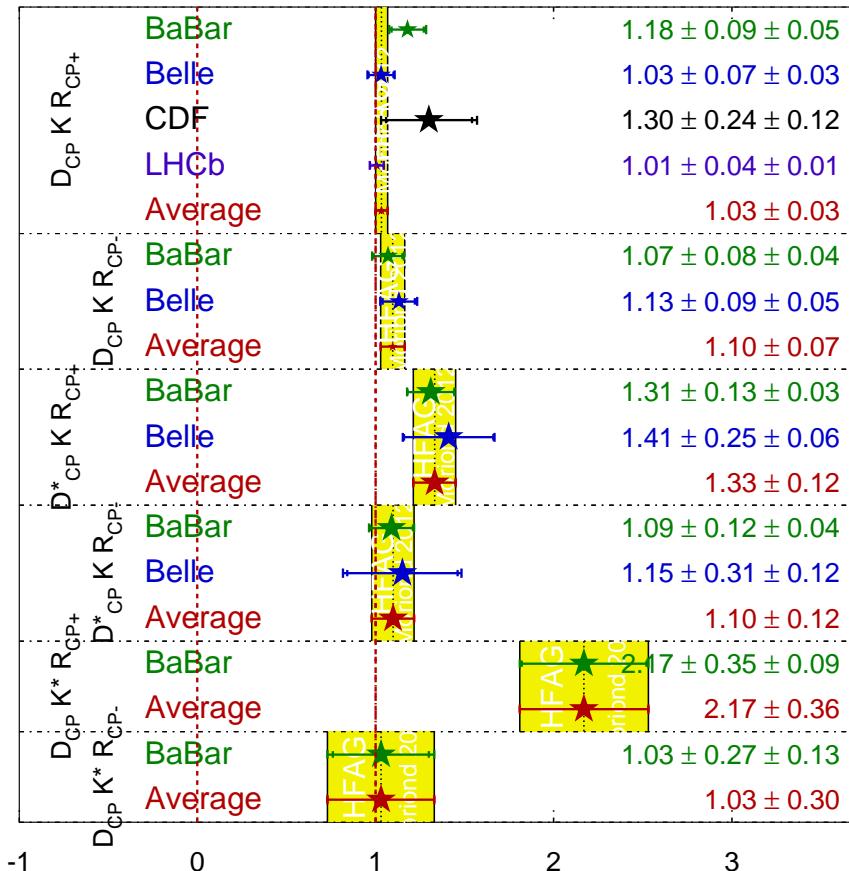
$$R_{CP-} = (8.29 \pm 0.63)\%$$

$$A_{CP-} = (-12.4 \pm 6.4)\%$$

ϕ_3 With GLW

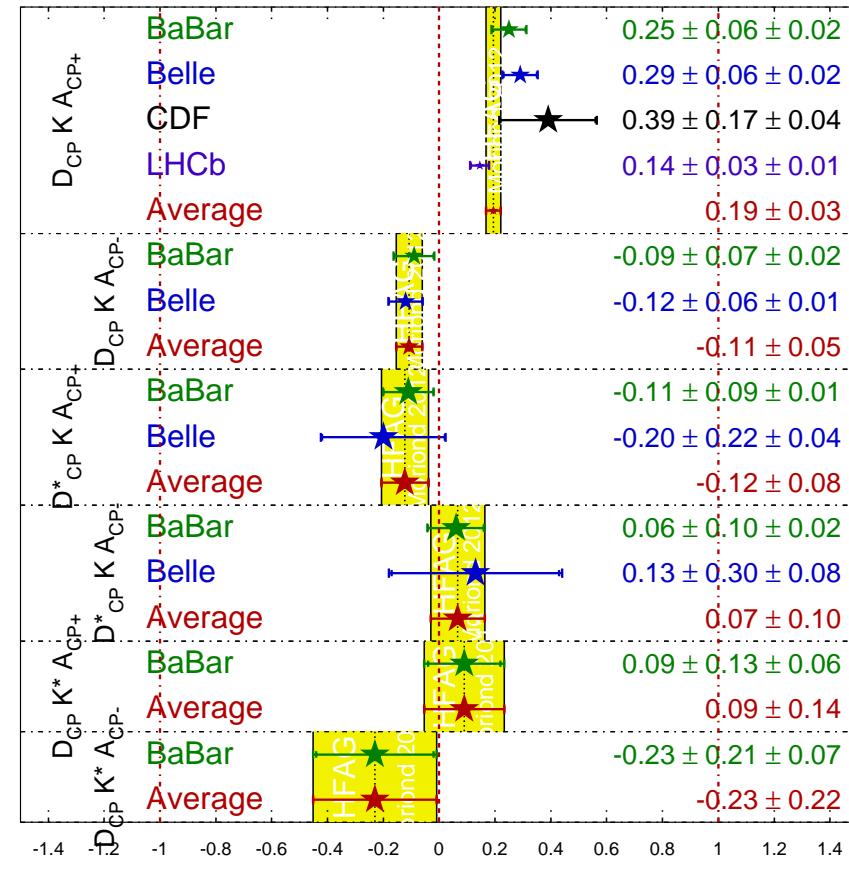
R_{CP} Averages

HFAG
Moriond 2012
PRELIMINARY



A_{CP} Averages

HFAG
Moriond 2012
PRELIMINARY



ϕ_3 With ADS

ADS method: $B^- \rightarrow DK^-$ with $D \rightarrow K^+\pi^-$ or similar

Favoured ($b \rightarrow c$) B decay followed by DCS D decay interferes with suppressed ($b \rightarrow u$) B decay followed by the CKM-favoured D decay

Measured observables

$$\mathcal{R}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]K^-) + \mathcal{B}([K^-\pi^+]K^+)}{\mathcal{B}([K^-\pi^+]K^-) + \mathcal{B}([K^+\pi^-]K^+)}$$
$$\mathcal{A}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]K^-) - \mathcal{B}([K^-\pi^+]K^+)}{\mathcal{B}([K^+\pi^-]K^-) + \mathcal{B}([K^-\pi^+]K^+)}$$

Relationship between observables constrain ϕ_3

$$\mathcal{R}_{DK} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \phi_3$$

$$\mathcal{A}_{DK} = \frac{2r_B r_D \sin(\delta_B + \delta_D) \sin \phi_3}{\mathcal{R}_{DK}}$$

Amplitude ratio: $r_D = \frac{A(D^0 \rightarrow K^+\pi^-)}{A(\bar{D}^0 \rightarrow K^+\pi^-)}$

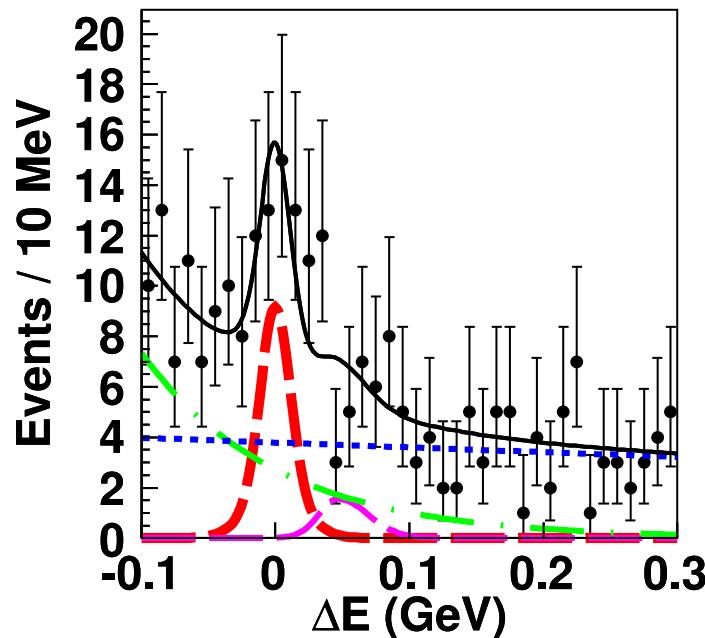
Strong phase difference, δ_D

ϕ_3 With ADS

Fit event shape Neural Network for better discrimination from dominant continuum background

Belle: PRL 106, 231803 (2011)

$$D \rightarrow K^+ \pi^-$$



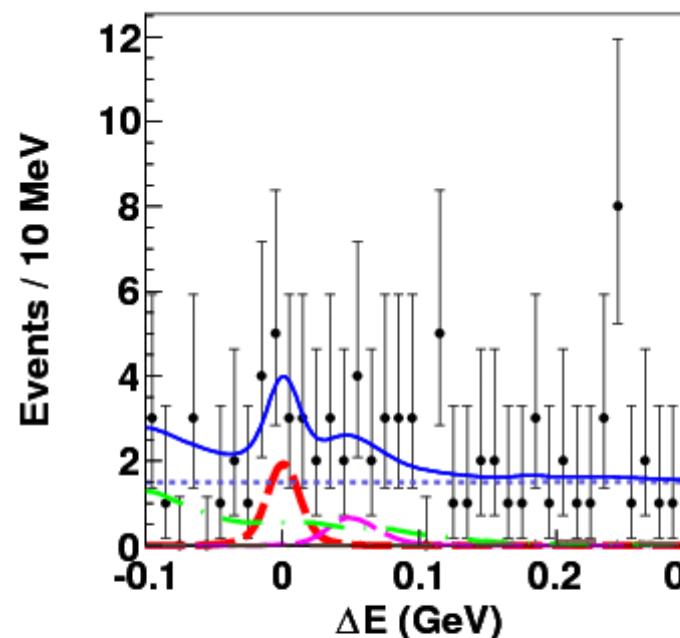
Redb: Signal

$$\mathcal{R}_{DK} = (1.63^{+0.44+0.07}_{-0.41-0.13}) \times 10^{-2}$$

$$\mathcal{A}_{DK} = -0.39^{+0.26+0.04}_{-0.28-0.03}$$

Belle: Preliminary

$$D^{*0} \rightarrow D\pi^0, D \rightarrow K^+ \pi^-$$



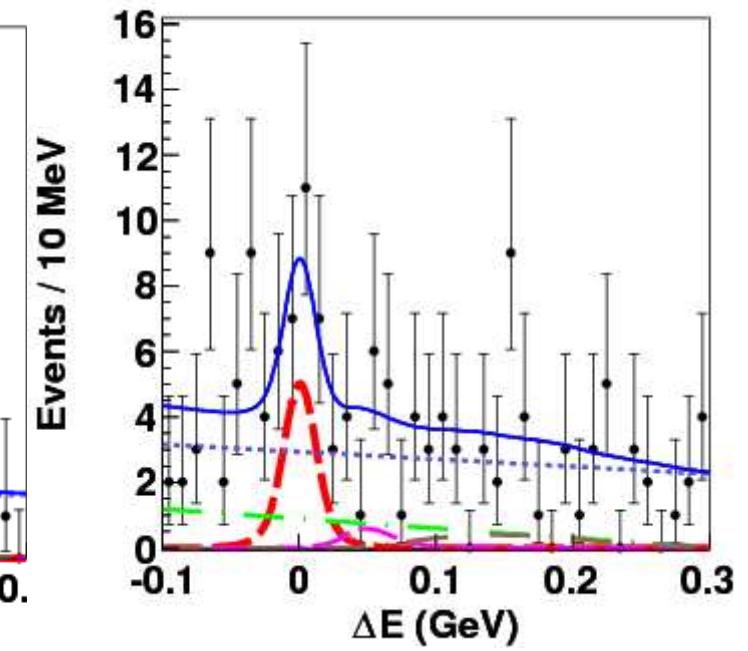
Red: Signal

$$\mathcal{R}_{D\pi^0} = (1.0^{+0.8+0.1}_{-0.7-0.2}) \times 10^{-2}$$

$$\mathcal{A}_{D\pi^0} = +0.4^{+1.1+0.2}_{-0.7-0.1}$$

Belle: Preliminary

$$D^{*0} \rightarrow D\gamma, D \rightarrow K^+ \pi^-$$

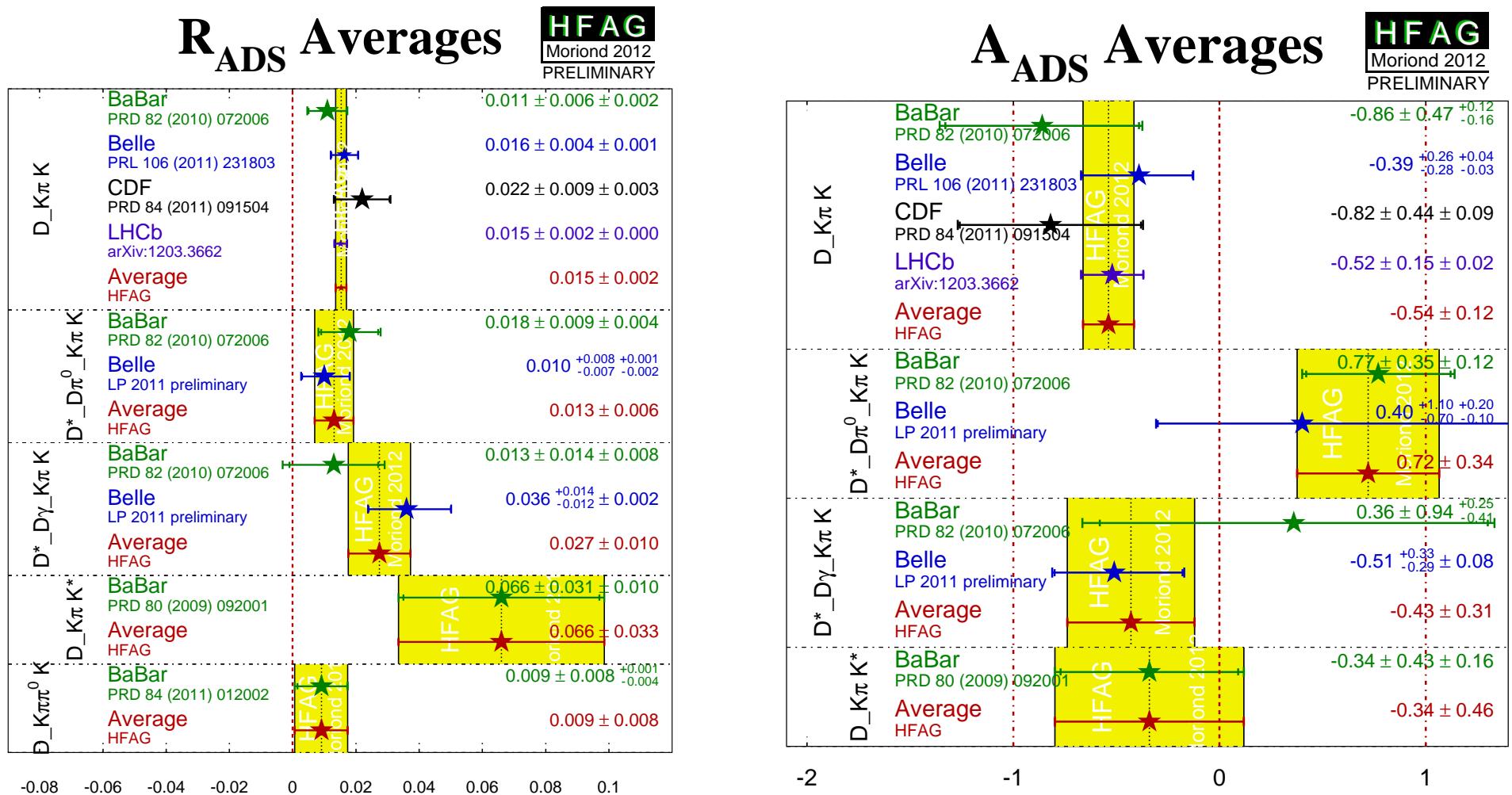


Red: Signal $\mathcal{R}_{D\gamma} =$

$$(3.6^{+1.4}_{-1.2} \pm 0.2) \times 10^{-2}$$

$$\mathcal{A}_{D\gamma} = -0.51^{+0.33}_{-0.29} \pm 0.08$$

ϕ_3 With ADS

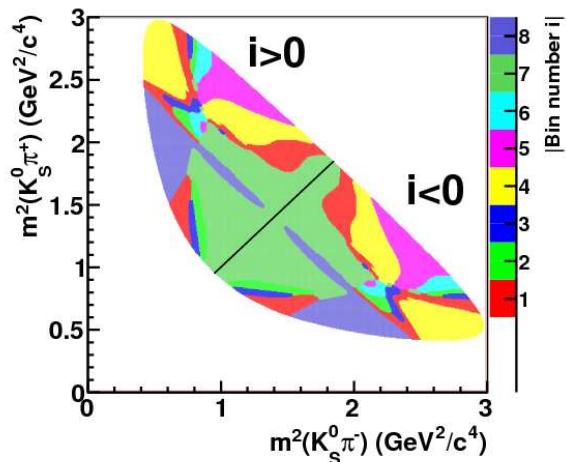


ϕ_3 With GGSZ

GGSZ method: Fit Dalitz plot of D decay to simultaneously determine r_B , δ_B and ϕ_3

However, model uncertainty is dominant systematic error \leadsto remove with binned Dalitz method

Choice of binning affects ϕ_3 precision, but not ϕ_3 itself



Measure yield in each bin i

And compare in a χ^2 fit with

$$N_i^\pm = h_B [K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i + y_\pm s_i)]$$

$$x_\pm = r_B \cos(\delta_B \pm \phi_3), y_\pm = r_B \sin(\delta_B \pm \phi_3)$$

N_i^\pm : Expected number of $B^\pm \rightarrow D K^\pm$ events in bin i

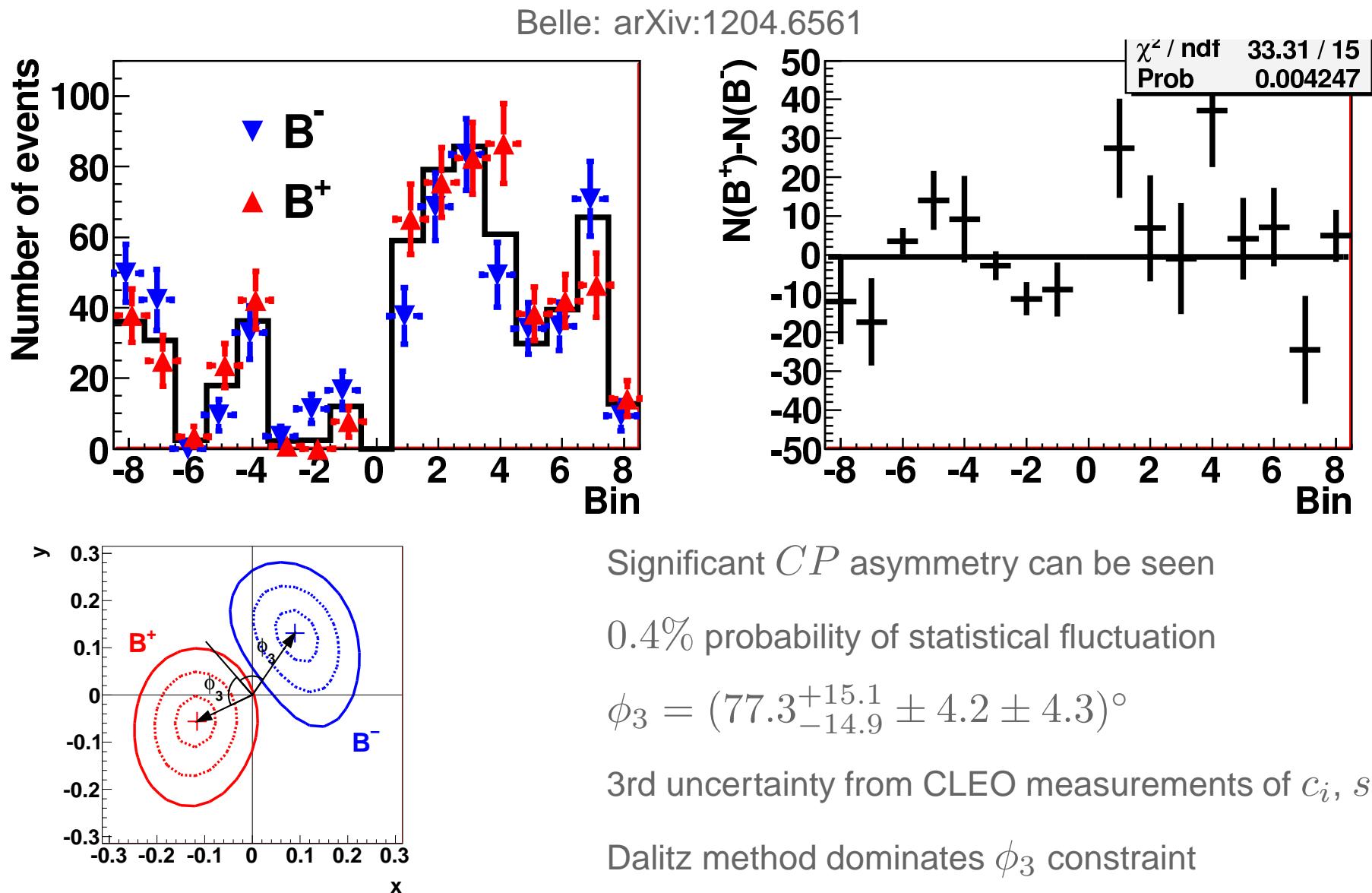
K_i : Number of events in bin i determined from a flavour-tagged sample ($D^{*\pm} \rightarrow D\pi^\pm$)

c_i, s_i : related to average strong phase difference in bin i

$$c_i = \langle \cos \Delta\delta_D \rangle_i, s_i = \langle \sin \Delta\delta_D \rangle_i$$

Measured by CLEO with $\psi(3770) \rightarrow D^0 \bar{D}^0$, can also be measured at BES-III

ϕ_3 With GGSZ



Summary

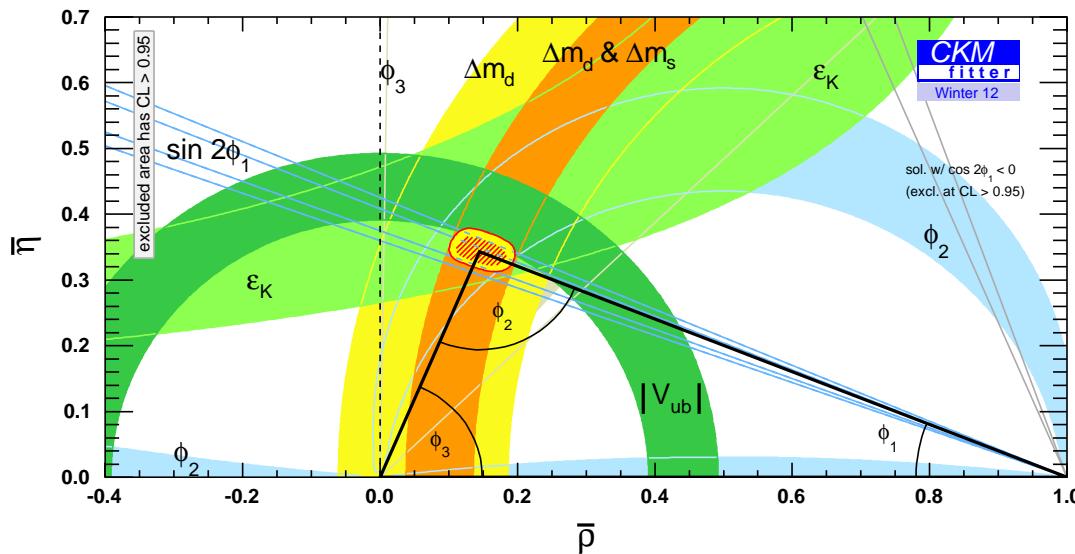
New final results from Belle

First evidence of CP violation in $B^0 \rightarrow a_1(1260)^\pm \pi^\mp$

Measurements GLW and ADS parameters

GGSZ method most powerful for determining ϕ_3 , model independent approach promising

More final results on ϕ_2 and ϕ_3 expected soon



$$\phi_2 = (88.7^{+4.6}_{-4.2})^\circ$$

$$\phi_3 = (66 \pm 12)^\circ$$

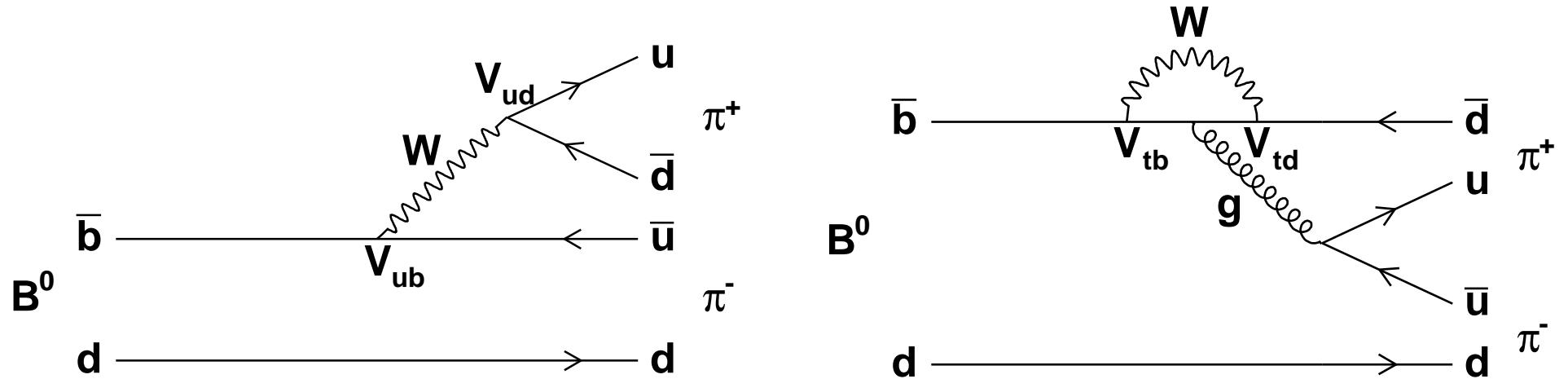
Hi Oskana! :P

Backup

Isospin Analysis

Can recover ϕ_2 with an SU(2) isospin analysis

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



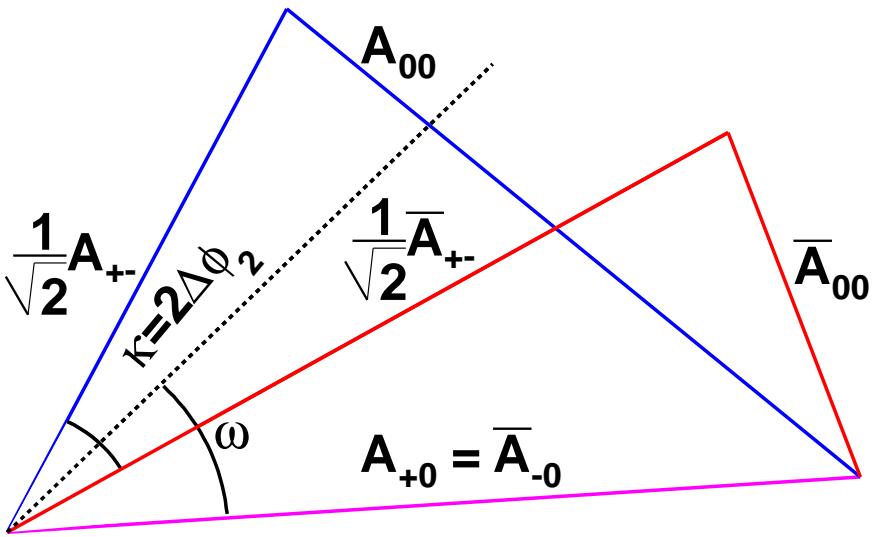
Consider $B^+ \rightarrow \pi^+ \pi^0$ which has $I_3 = 1 \Rightarrow$ Isospin, $I = 1, 2$

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

Isospin Analysis



2-fold ambiguity of ϕ_2 in measured S_{CP} , therefore 8-fold ambiguity in ϕ_2 in isospin analysis

Fully determined from 6 physical observables

$$\mathcal{B}(B^0 \rightarrow \rho^+ \rho^-), \mathcal{B}(B^0 \rightarrow \rho^0 \rho^0), \mathcal{B}(B^+ \rightarrow \rho^+ \rho^0)$$

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

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

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

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

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

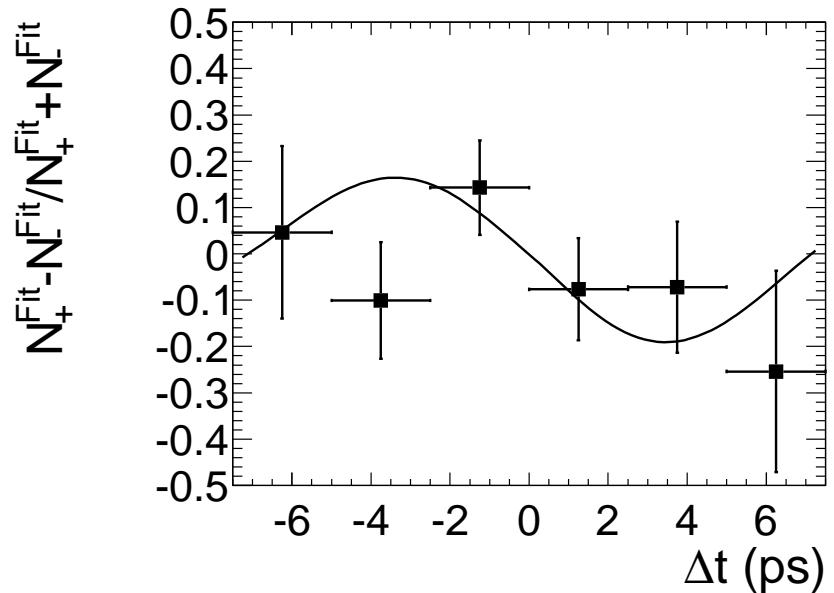
Neglecting electroweak penguins, $A_{+0} = \bar{A}_{-0}$

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

$$B^0 \rightarrow a_1(1260)^\pm \pi^\mp$$

“Disagreement” with BaBar on \mathcal{S}_{CP}
Belle

$$\mathcal{S}_{CP} = -0.51 \pm 0.14 \text{ (stat)} \pm 0.08 \text{ (syst)}$$



$$a_{CP}(\Delta t) \propto \mathcal{S}_{CP} \sin \Delta m_d \Delta t - \mathcal{C}_{CP} \cos \Delta m_d \Delta t$$

Either we disagree on the definition of asymmetry

Or BaBar’s curve shows that \mathcal{S}_{CP} should be negative

BaBar

$$\mathcal{S}_{CP} = +0.37 \pm 0.21 \text{ (stat)} \pm 0.07 \text{ (syst)}$$

