ϕ_2 (α) and ϕ_3 (γ)
– mini-review –

Moriond EW
March 10-17 2007, La Thuile, Italy

Akito KUSAKA (Univ. of Tokyo)
for Belle and BaBar collaborations

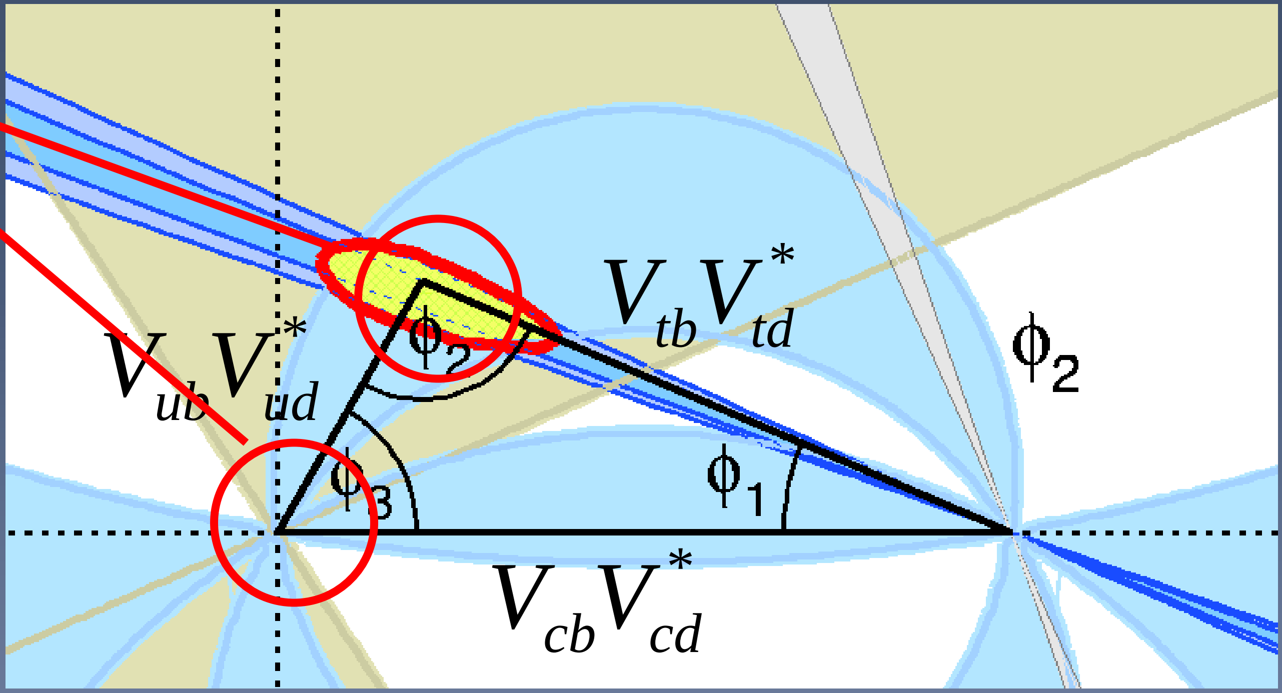
Outline

- Introduction
- ϕ_2 (α)
  - $B \rightarrow \pi\pi$, $B \rightarrow \rho\rho$, $B \rightarrow \rho\pi$
  - $B \rightarrow a_1 \pi$
- ϕ_3 (γ)
  - Dalitz plot analysis
  - GLW and ADS methods
  - $\sin(2\phi_1+\phi_3)$: $B^0 \rightarrow D^{(*)\pm\mp} \pi^{\mp\pm}$
- Summary

Introduction
– Unitarity Triangle

This talk

$\phi_1 \equiv \beta$
$\phi_2 \equiv \alpha$
$\phi_3 \equiv \gamma$

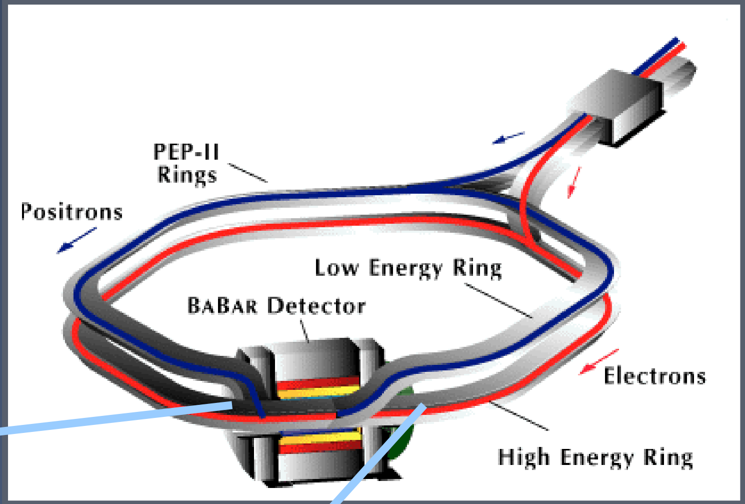


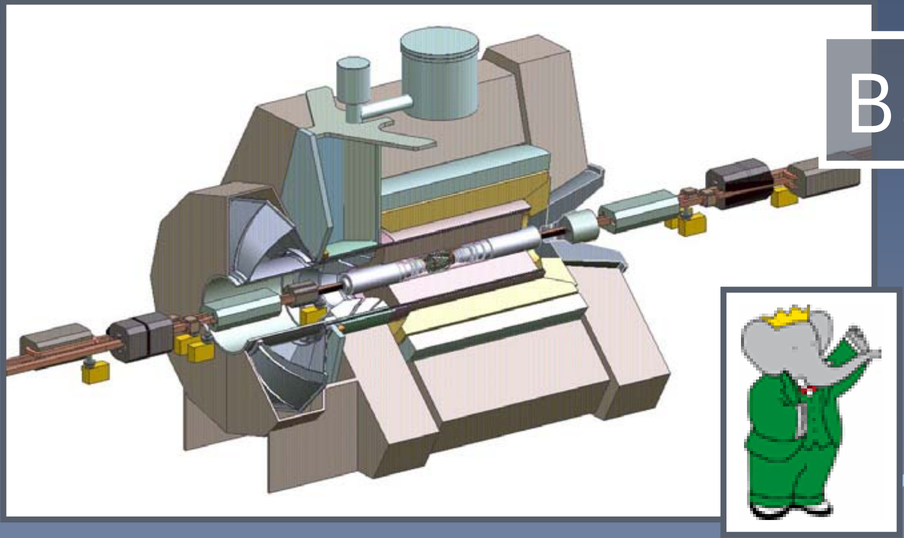
Provided by CKM fitter

Introduction
– BaBar/PEP-II

PEP-II at SLAC

9GeV (e^-) × 3.1GeV (e^+)
peak luminosity:
$1.21 \times 10^{34} cm^{-2}s^{-1}$





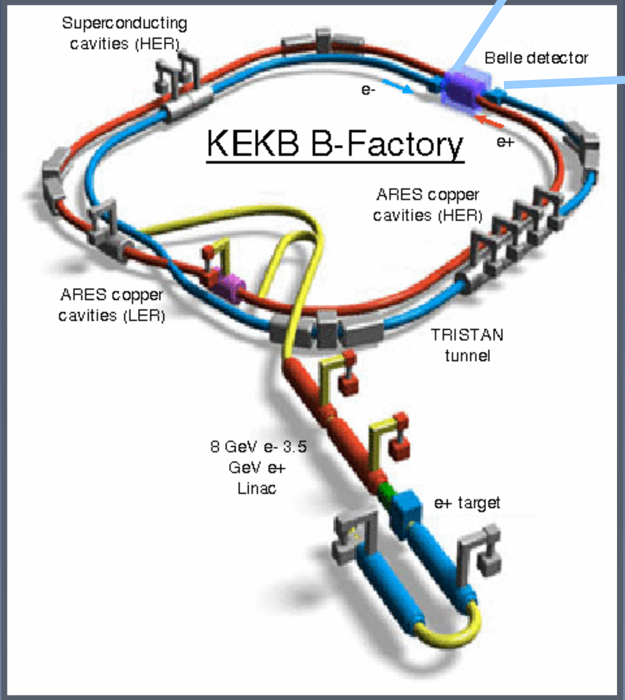
BaBar

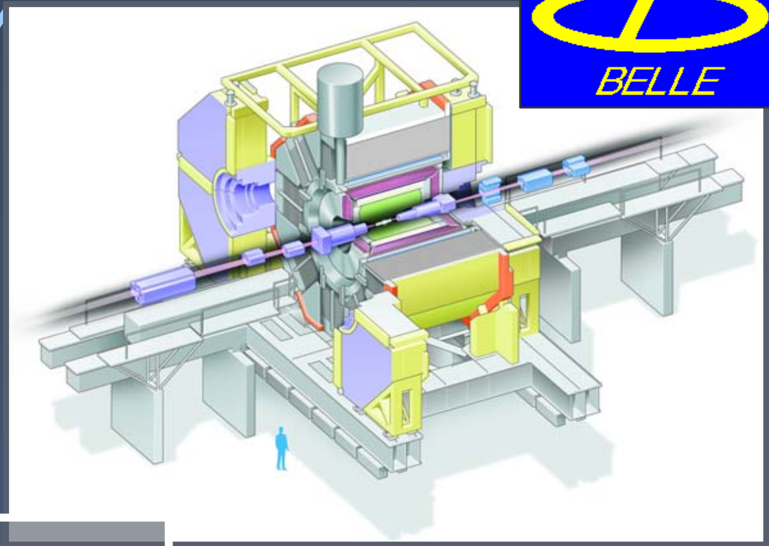
11 Countries
60 Institutes
~600 Physicists

Introduction
– Belle/KEKB

KEKB at KEK

8GeV (e^-) × 3.5GeV (e^+)
peak luminosity:
$1.71\times10^{34}cm^{-2}s^{-1}$





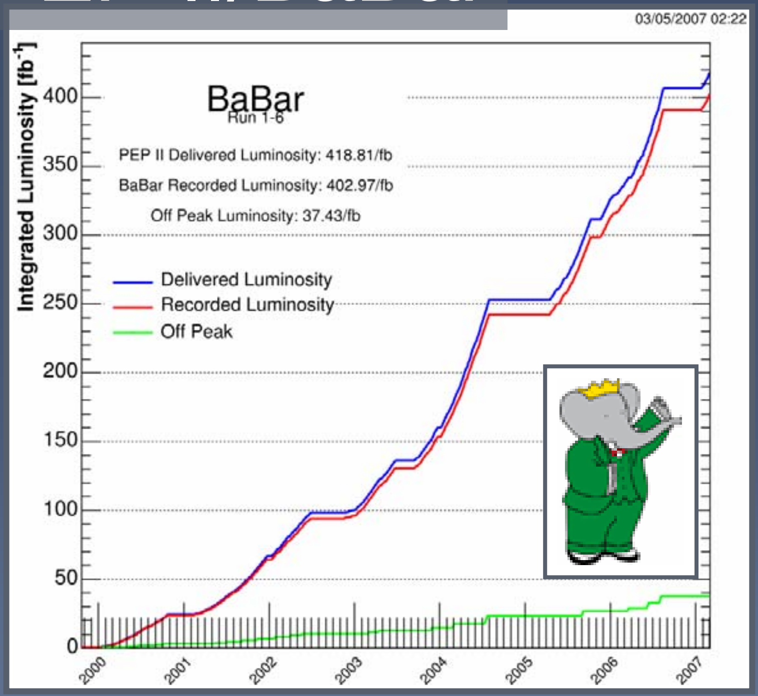
Belle

13 Countries
55 Institutes
~400 Collaborators

Crab Cavity has been installed in 2007 winter!!

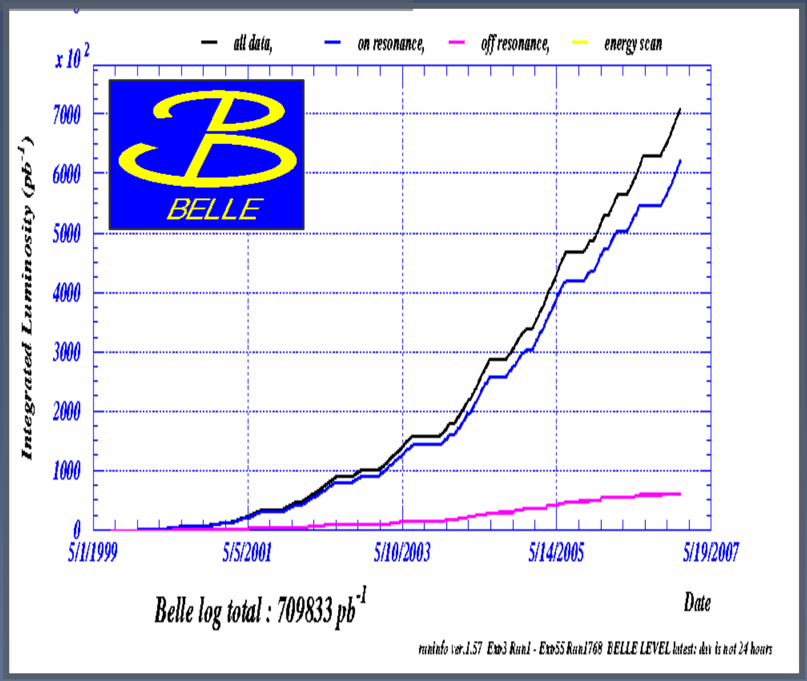
Introduction
– Luminosity of *B*-factories

PEP-II/BaBar



~400 fb^{-1}

KEKB/Belle

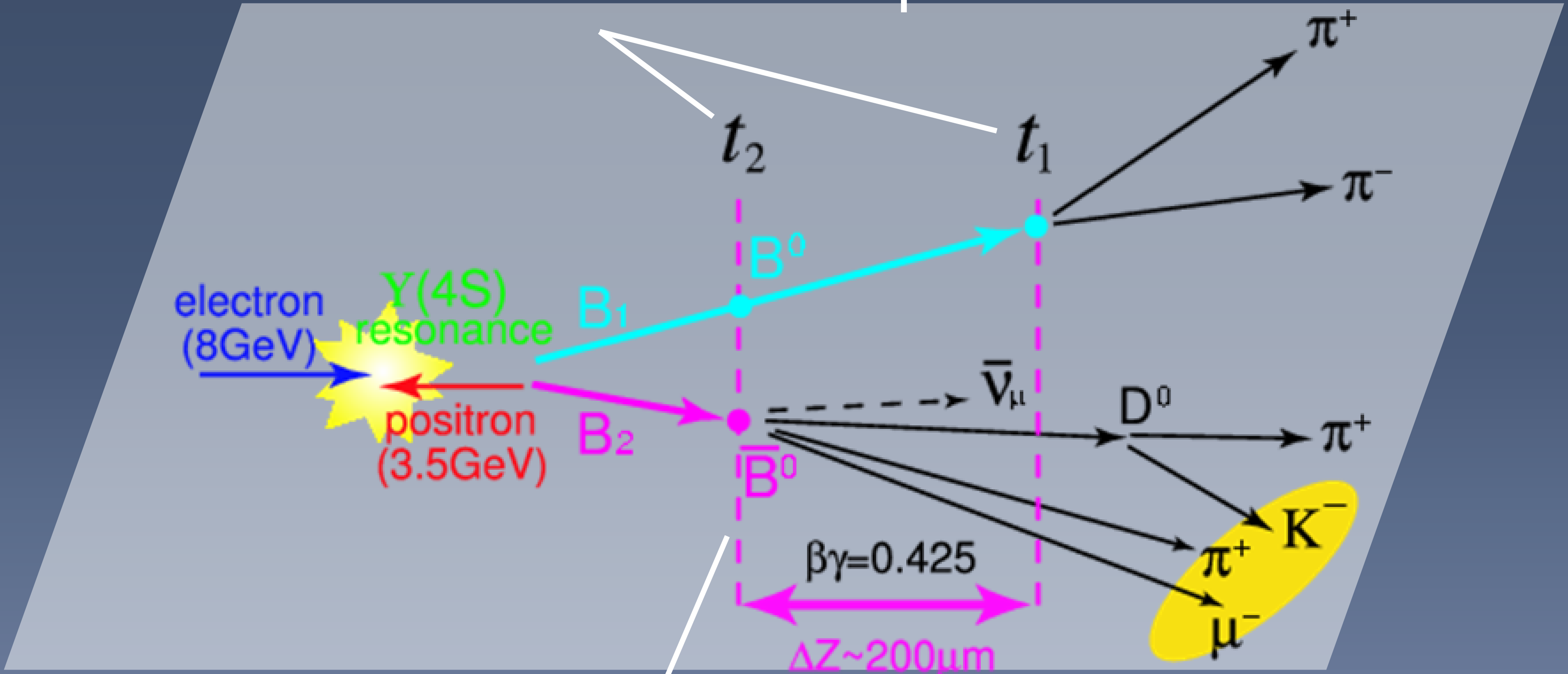


~700 fb^{-1}

B-factories have entered the era of ab^{-1}!!

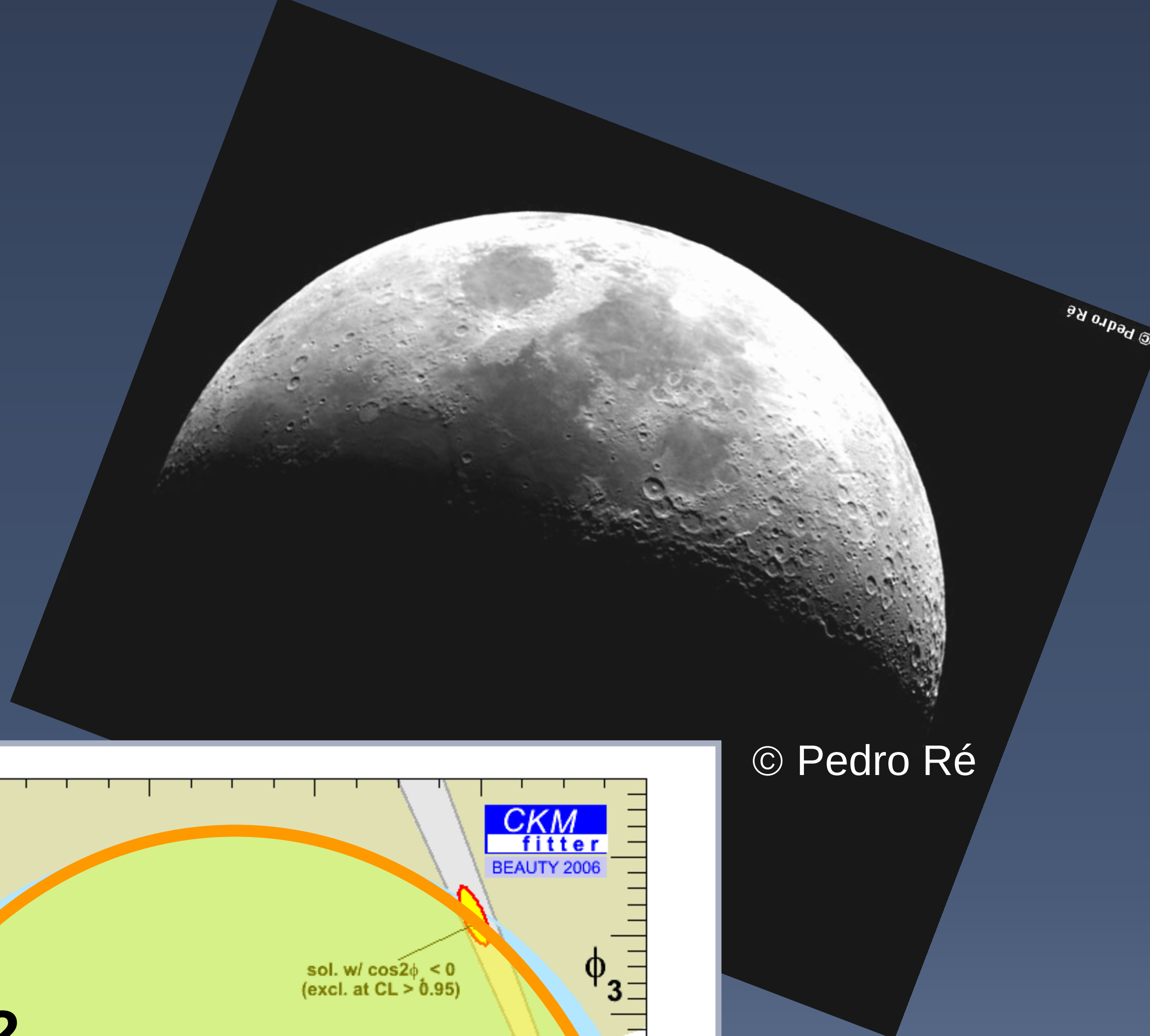
Introduction
– Strategy (time-dependent)

B's are boosted
→ Δt is measured from vertex positions

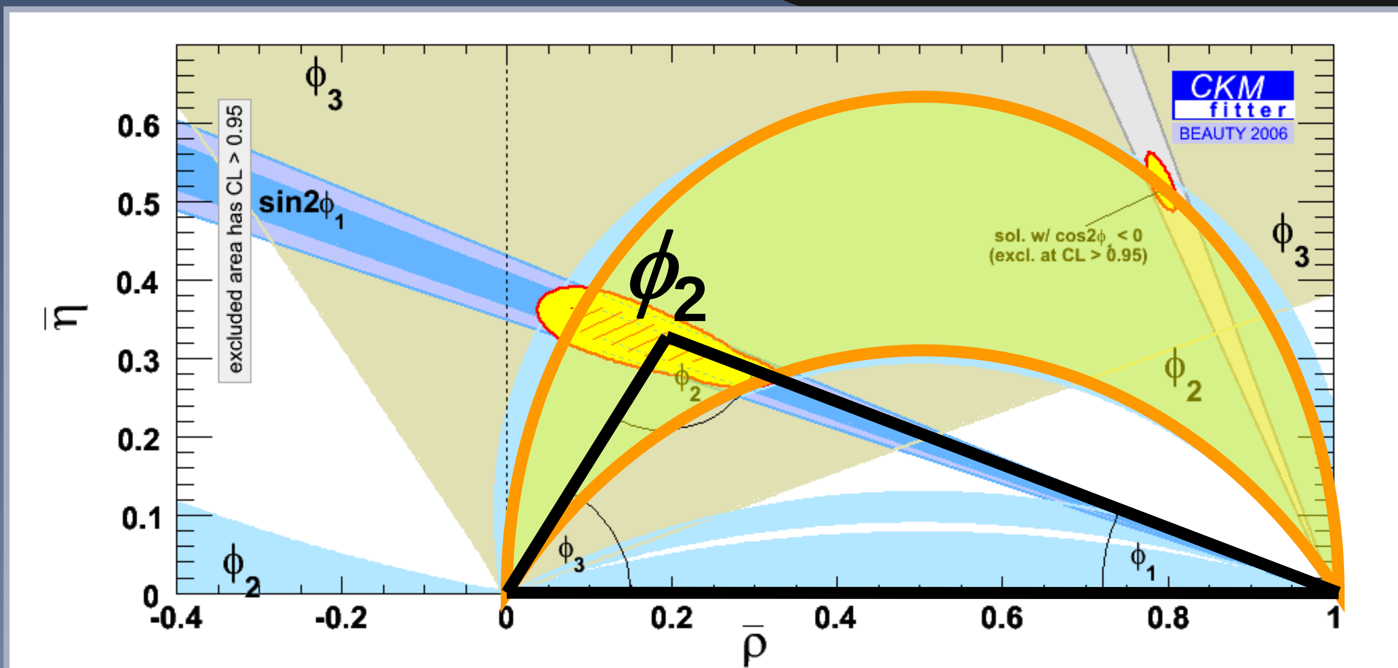


B's are entangled
→ flavor of B_1 at time t_2 is determined by B_2 decay

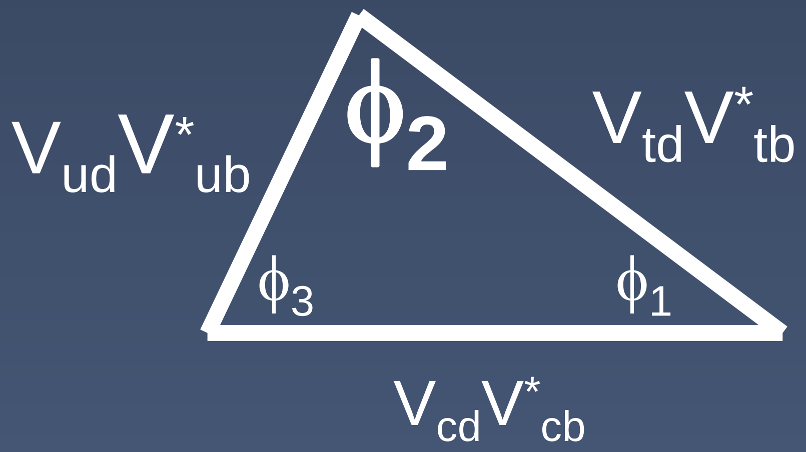
$\phi_2\ (\alpha)$

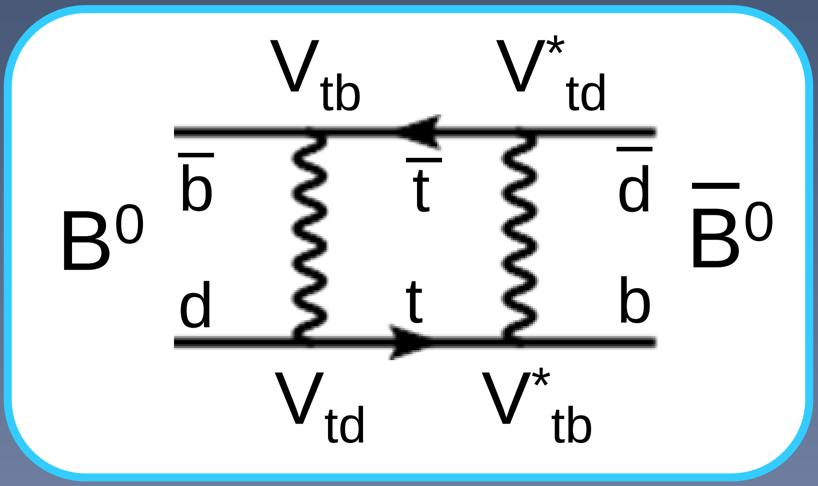


© Pedro Ré

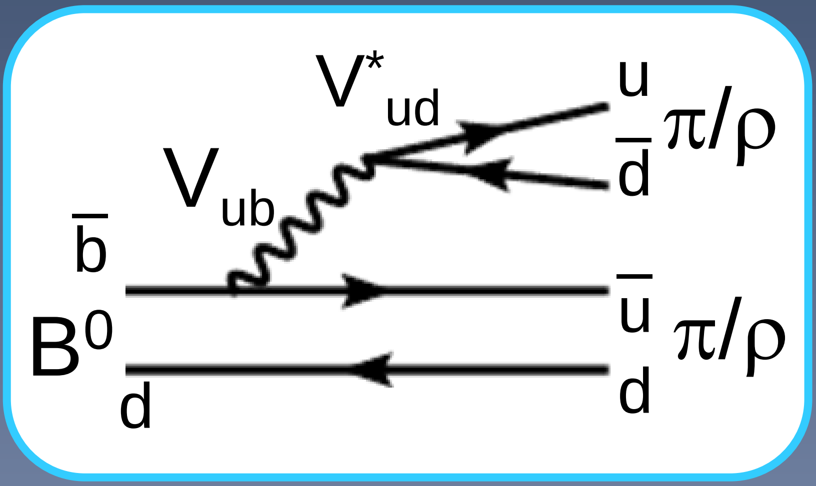


ϕ_2 (α) – How to Measure?



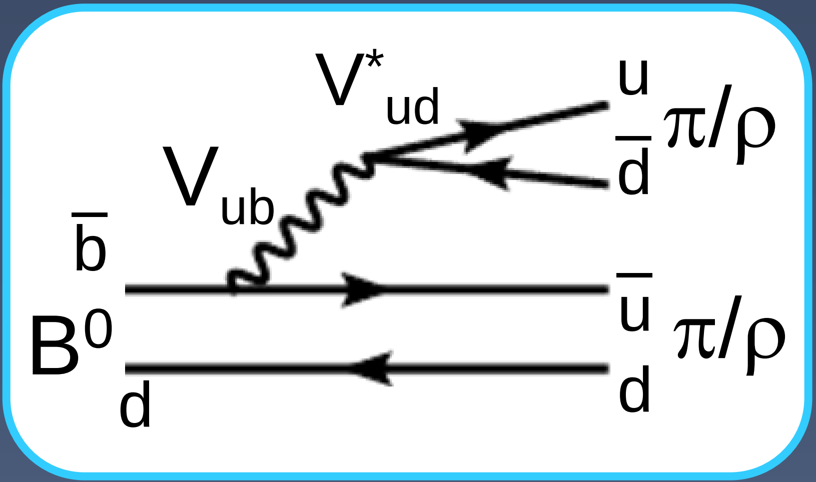


Mixing diagram



Decay diagram (tree)

ϕ_2 (α)
– How to Measure?



Decay diagram (tree)

Possible Decay Processes

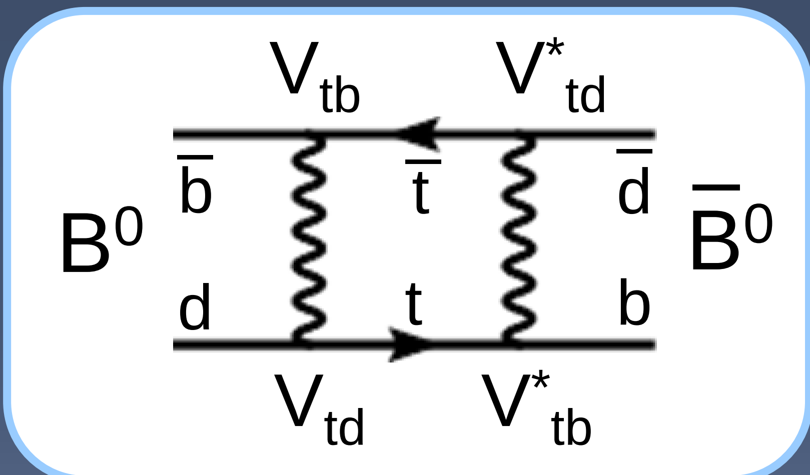
$B^0 \rightarrow \pi^+\pi^-$

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

$B^0 \rightarrow \rho^{+-}\pi^{-+}$

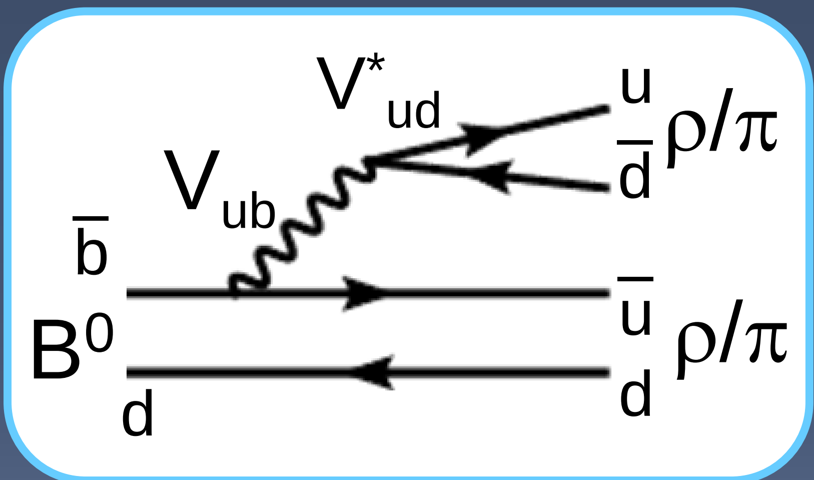
$B^0 \rightarrow a_1^{+-}\pi^{-+}$

ϕ_2 (α) – Penguin Contamination



Mixing diagram

+



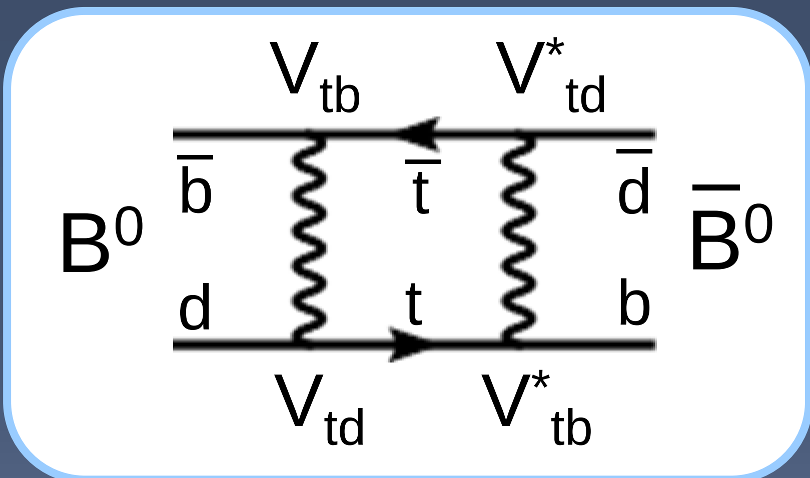
Tree diagram

ϕ_2

ϕ_2

ϕ_2 (α)

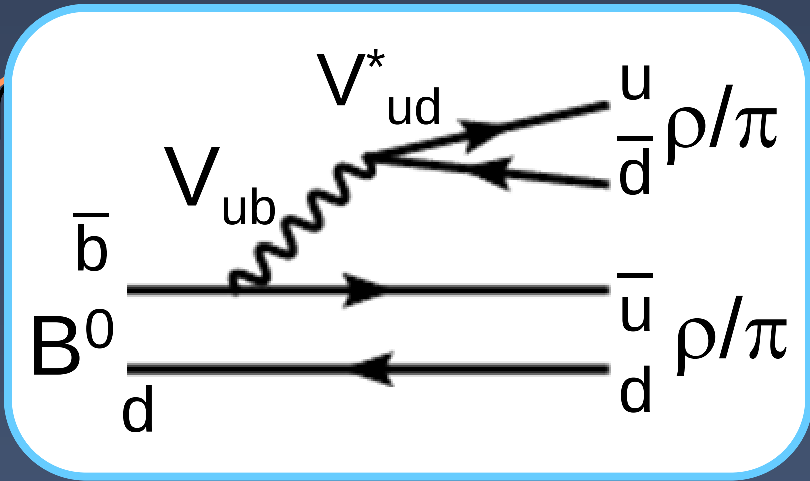
– Penguin Cor



Mixing diagram

ϕ_2^{eff}

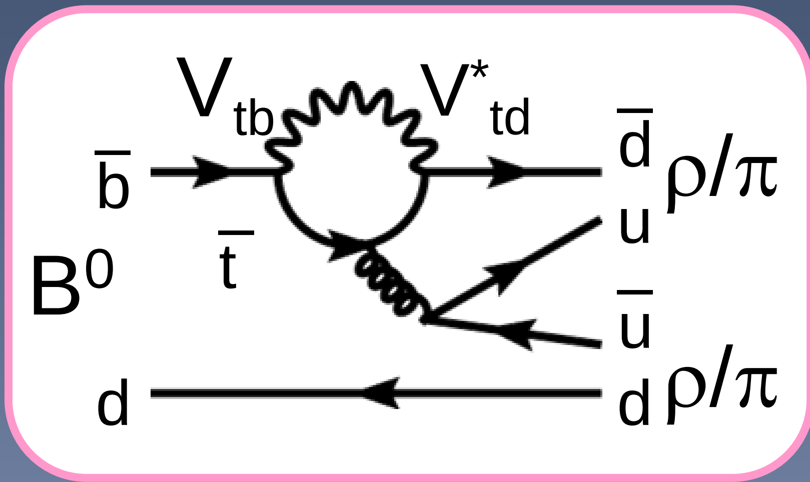
+



Tree diagram

ϕ_2

+



Penguin diagram

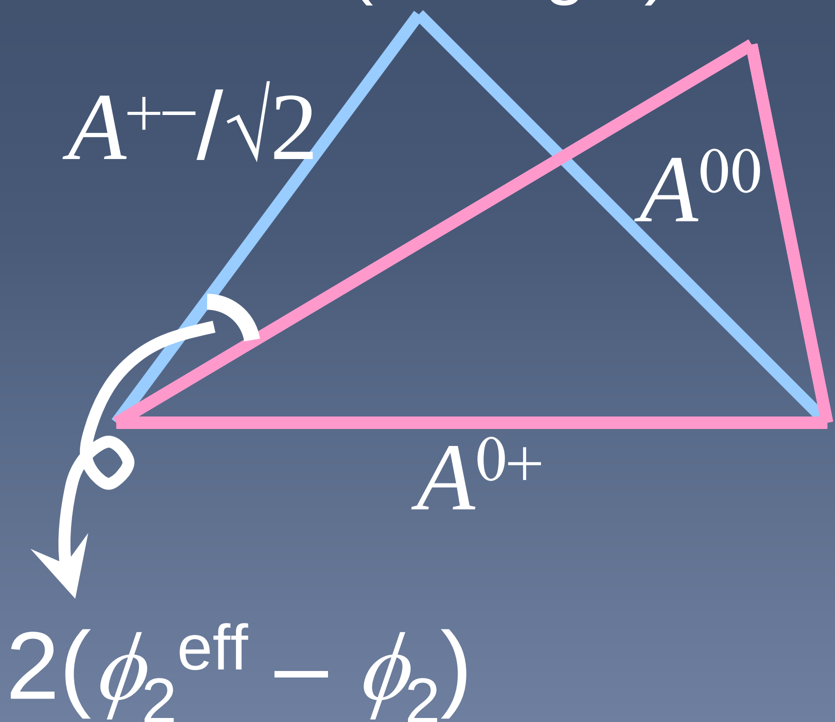
0

ϕ_2 (α) – Isospin Relations

Gronau & London (1990)
Lipkin *et. al.* (1991)
Gronau (1991)

$B \to \pi\pi$, $\rho\rho$

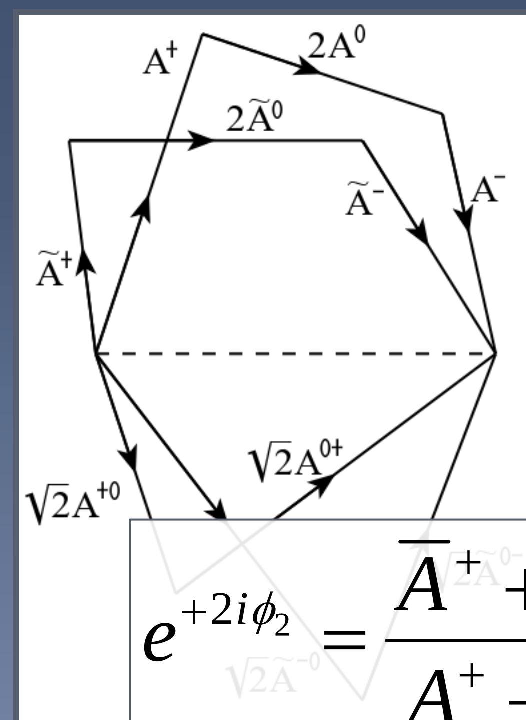
Isospin Analysis (Triangle)



$B \to \rho\pi$

Dalitz plot analysis

Isospin Analysis (Pentagon)



$$e^{+2i\phi_2} = \frac{\bar{A}^+ + \bar{A}^- + 2\bar{A}^0}{A^+ + A^- + 2A^0}$$

ϕ_2 (α)

– Remark: Two types of meas.

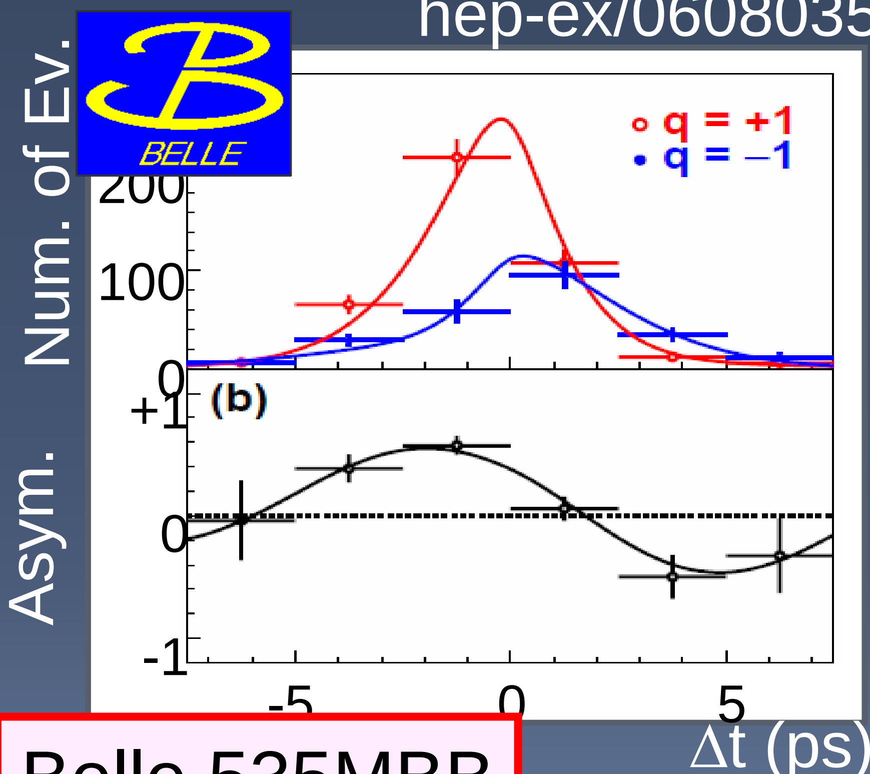
- Measurements of ϕ_2^{eff} (tCPV)
- Measurements for

  $|\phi_2 - \phi_2^{\mathrm{eff}}|$ (B.F., Asym.)

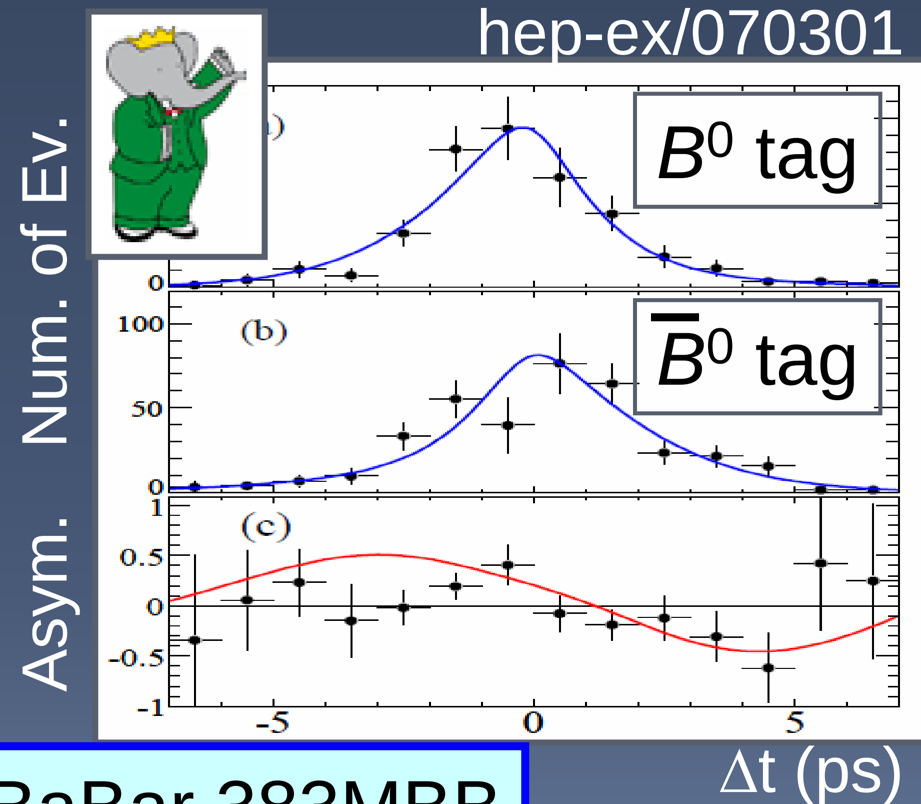
ϕ_2 (α)

– $B^0 \to \pi^+\pi^-$

hep-ex/0608035



hep-ex/070301



Belle 535MBB

$\mathcal{A}_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$

$\mathcal{S}_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$

BaBar 383MBB

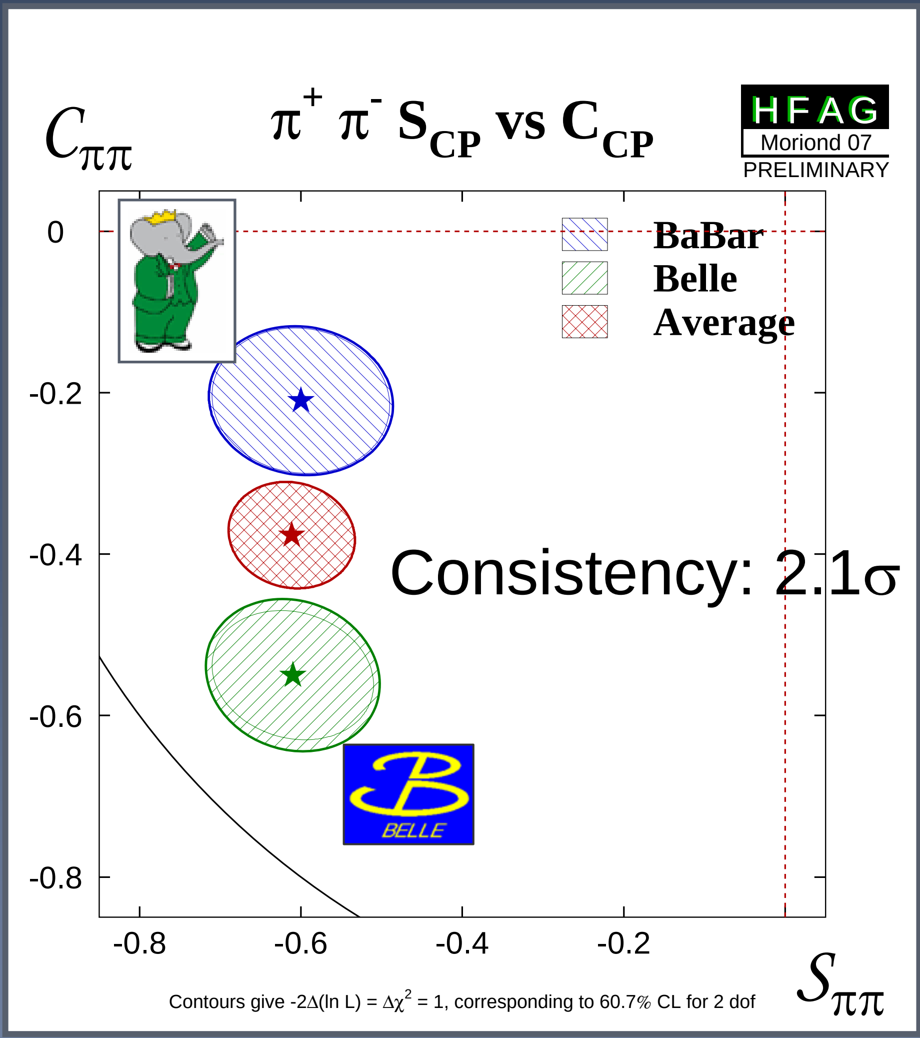
$C_{\pi\pi}\,(-\mathcal{A}_{\pi\pi}) = -0.21 \pm 0.09 \pm 0.02$

$\mathcal{S}_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03$

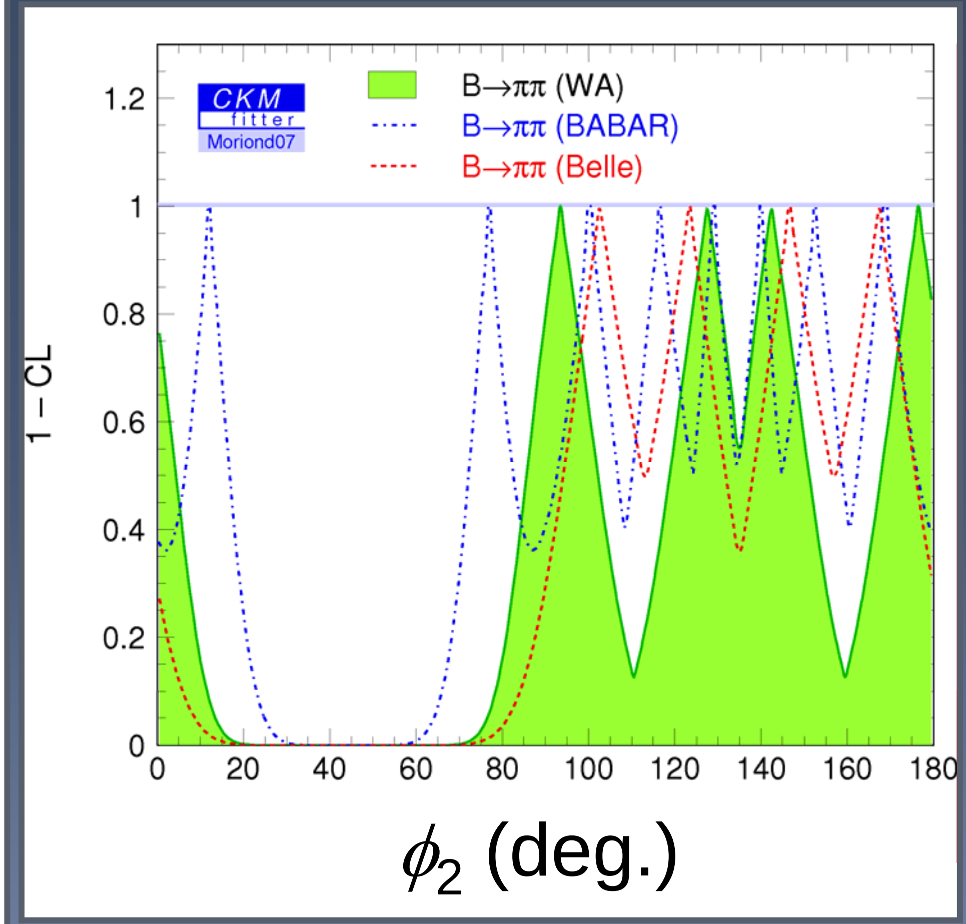
Direct CPV @ 5.5σ

CPV @ 5.5σ

ϕ_2 (α)
– $B^0 \rightarrow \pi\pi$



Constraint on ϕ_2

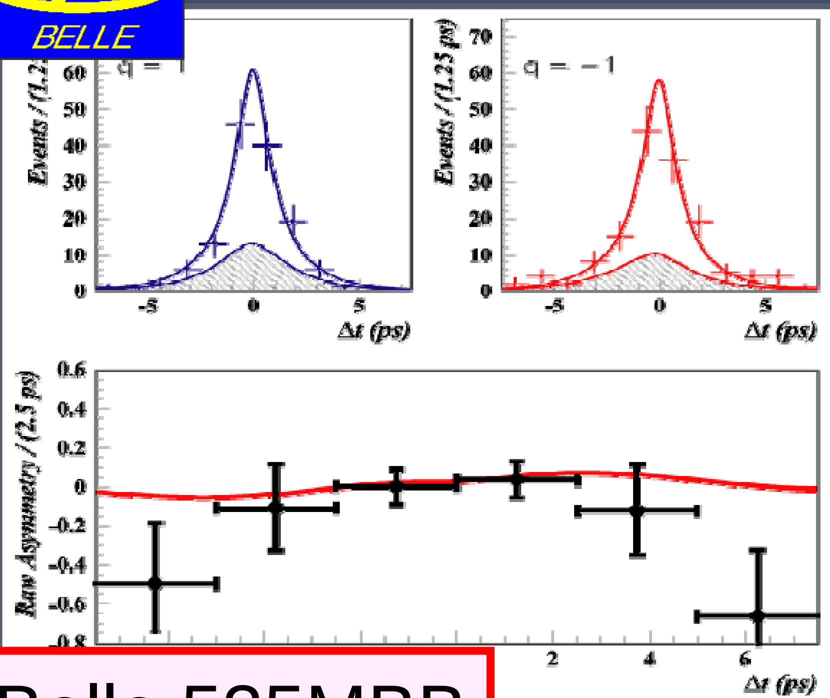


$$\phi_2 = 93.5^{+12.1}_{-10.0}$$

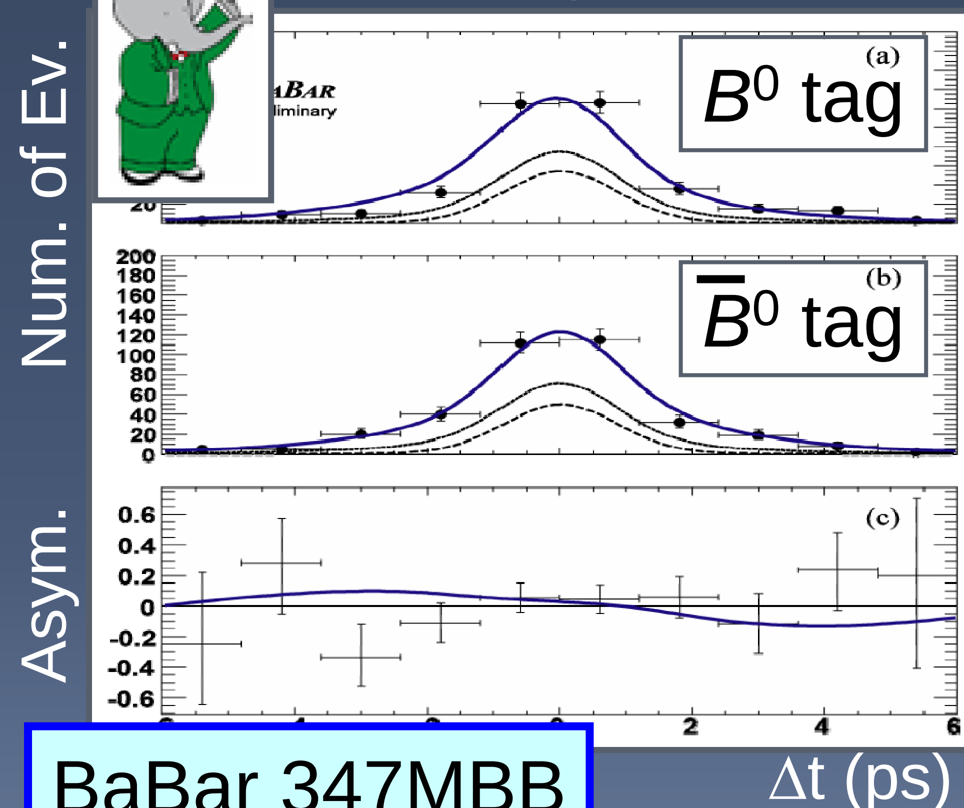
ϕ_2 (α) – $B^0 \to \rho^+\rho^-$

No CPV
→ ϕ_2~90° at no penguin limit

hep-ex/0702009



hep-ex/0607092



Belle 535MBB

$$\mathcal{A}_{\rho\rho} = +0.16 \pm 0.21 \pm 0.07$$

$$S_{\rho\rho} = +0.19\,^{+0.29}_{-0.30}\,^{+0.07}_{-0.06}$$

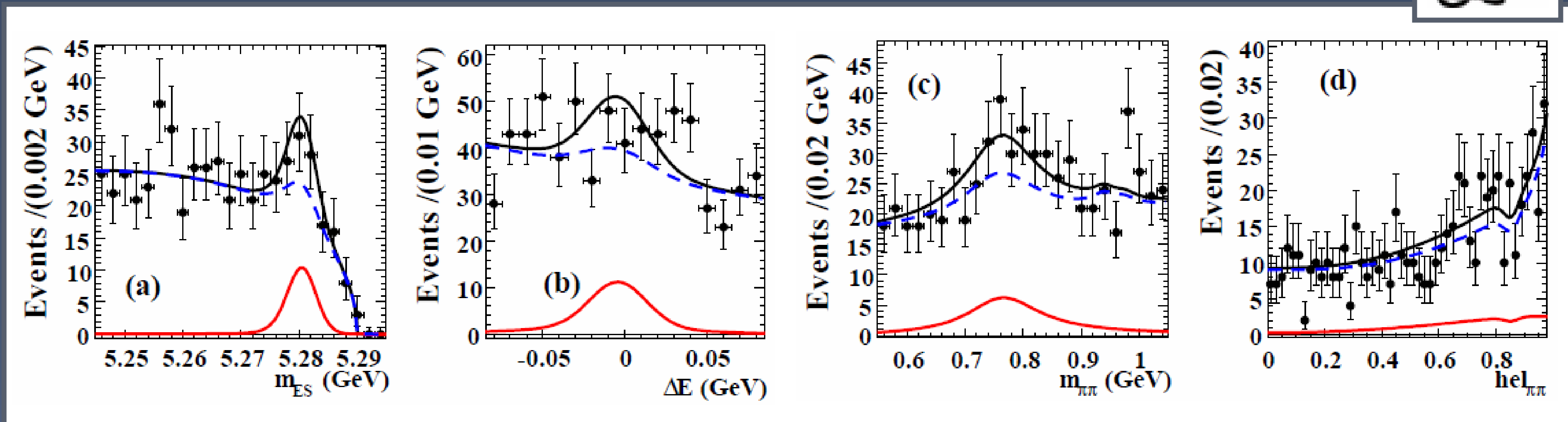
BaBar 347MBB

$$C_{\rho\rho} = -0.07 \pm 0.15 \pm 0.06$$

$$S_{\rho\rho} = -0.19 \pm 0.21\,^{+0.05}_{-0.07}$$

$\phi_2\,(\alpha)$

$-\ B^0 \rightarrow \rho^0 \rho^0$



BaBar 384MBB

3.5σ Evidence!

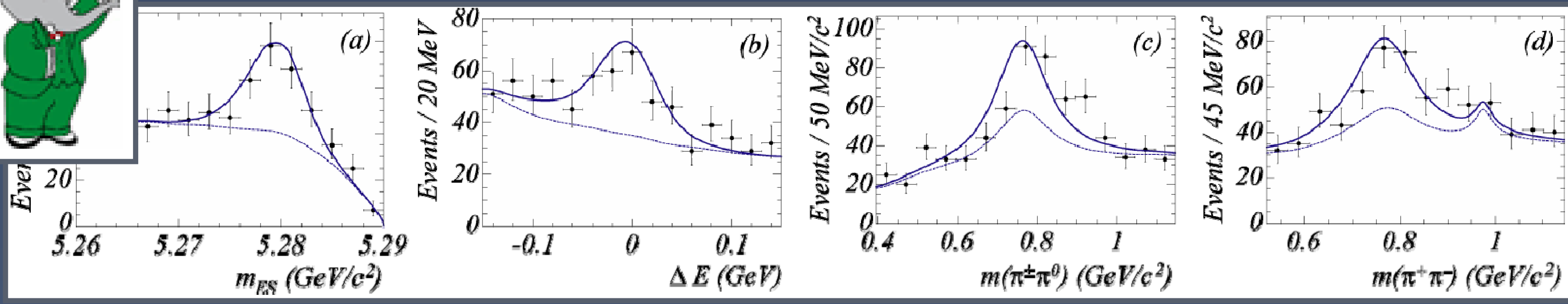
$$\mathcal{B} = (1.07 \pm 0.33 \pm 0.19) \times 10^{-6}$$

$$f_L = 0.87 \pm 0.13 \pm 0.04$$

hep-ex/0612021

ϕ_2 (α)

– $B^+ \rightarrow \rho^+ \rho^0$



BaBar 232MBB

$$\mathcal{B} = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$$

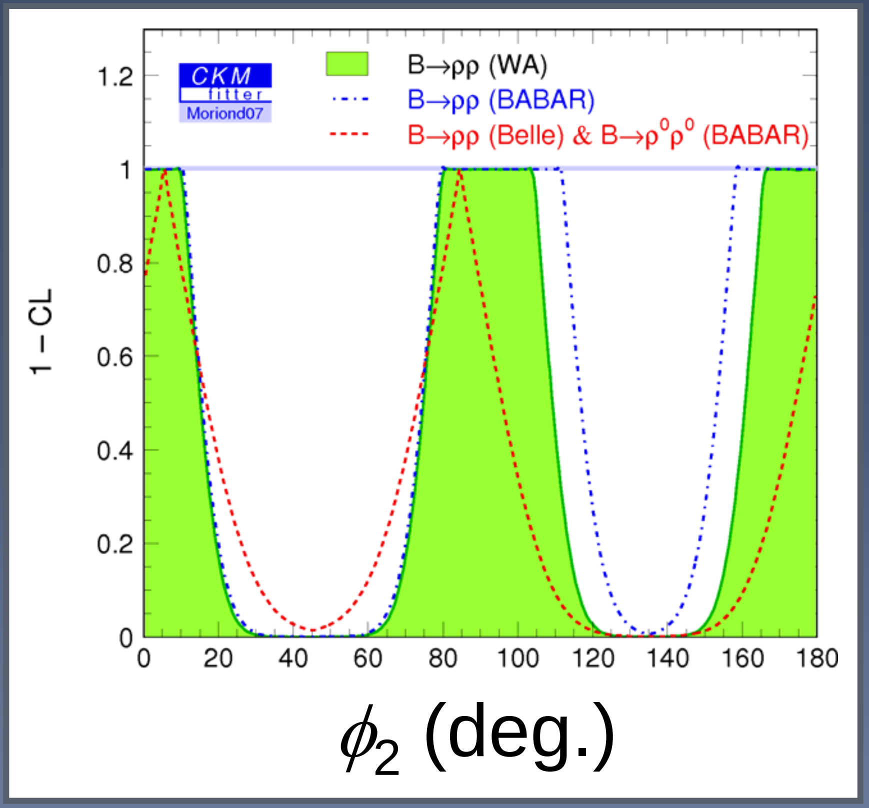
$$f_L = 0.905 \pm 0.042^{+0.023}_{-0.027}$$

$$\mathcal{A}_{CP} = -0.12 \pm 0.13 \pm 0.10$$

Phys.Rev.Lett. 97 (2006) 261801

ϕ_2 (α)
– $B^0 \rightarrow \rho\rho$

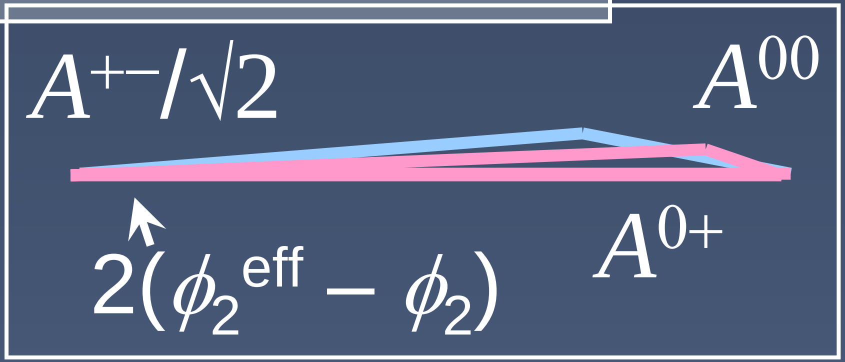
Constraint on ϕ_2



$\phi_2 = 92.0 \pm 19.5$

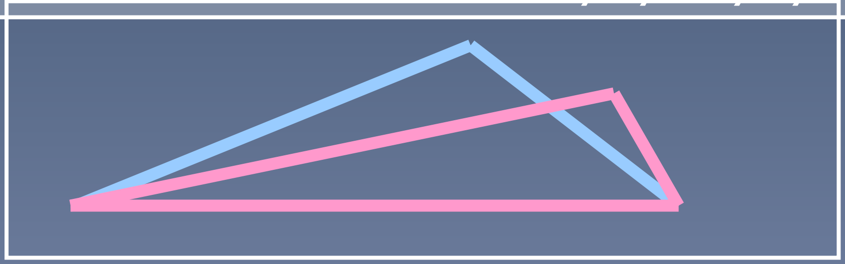
$B \rightarrow \rho\rho$ is not the best mode anymore

Before 2006 Summer



Triangles were squashed

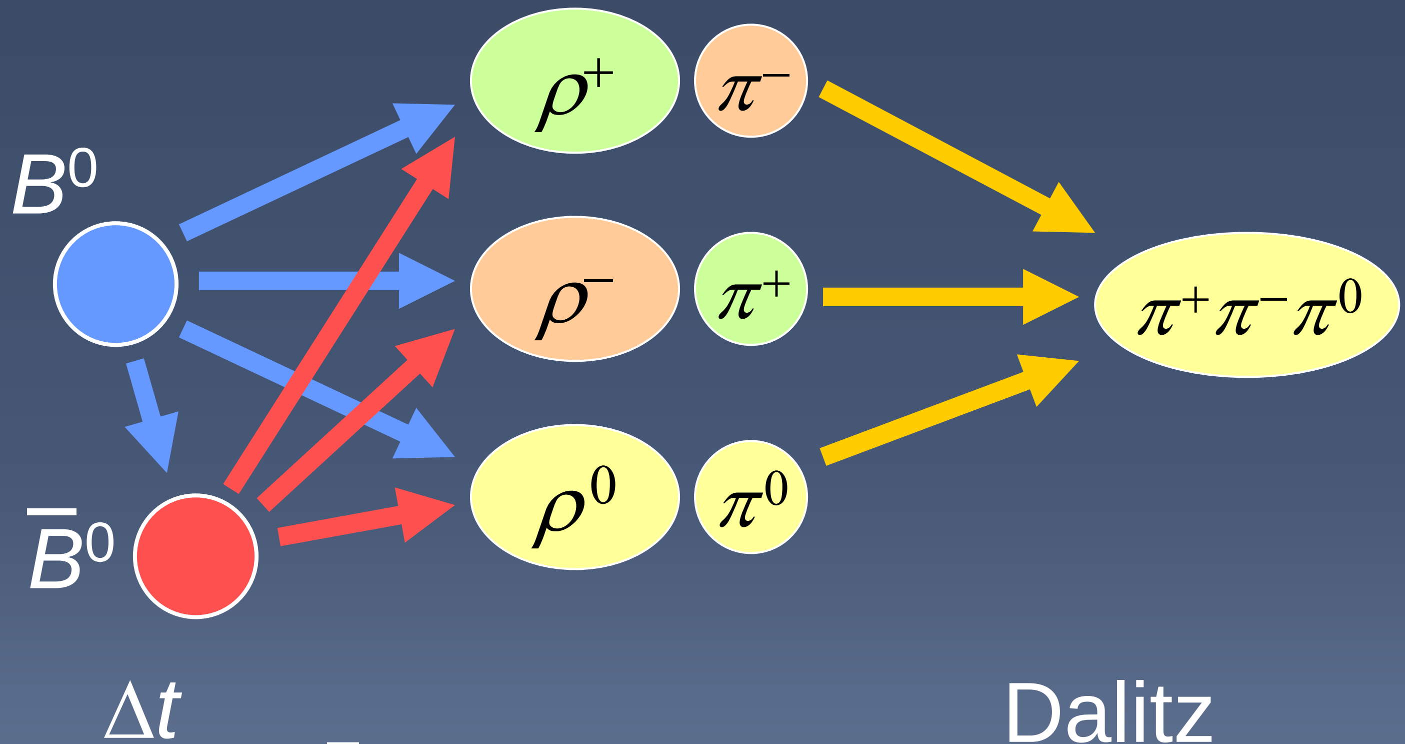
With New B.F. of $B \rightarrow \rho^0\rho^0$, $\rho^+\rho^0$



For further improvement, we need A_{CP} of $B^0 \rightarrow \rho^0\rho^0$.

ϕ_2 (α)

– $B^0 \rightarrow (\rho\pi)^0$ Dalitz Analysis



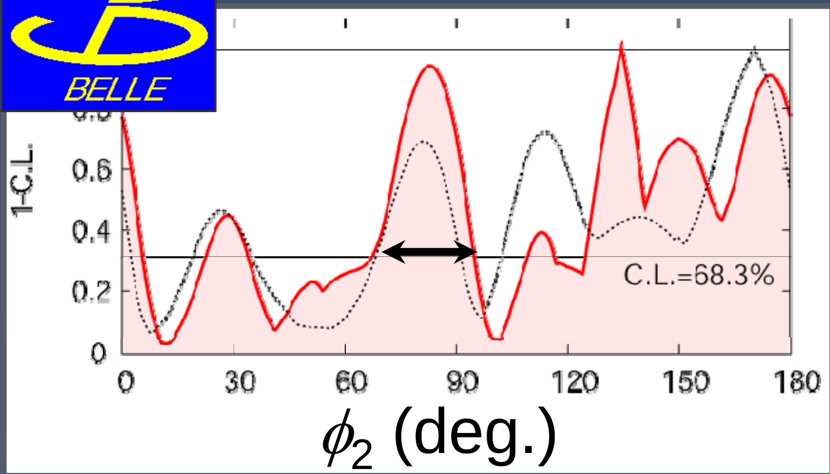
Interference by $B^0\bar{B}^0$ oscillation + Interference Between ρ^+, ρ^-, ρ^0

Various (24) Patterns of Interferences

→ Information on Relative Phases

ϕ_2 (α)
– $B^0 \rightarrow (\rho\pi)^0$ Dalitz Analysis

hep-ex/0701015

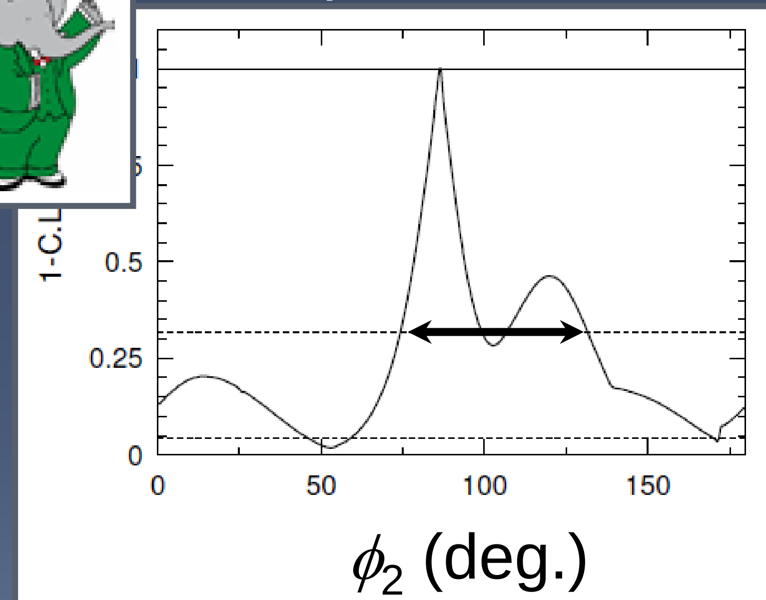


Dalitz + Pentagon Analysis

Belle 449MBB

$68° < \phi_2 < 95°$
with other
allowed regions

hep-ex/0703008

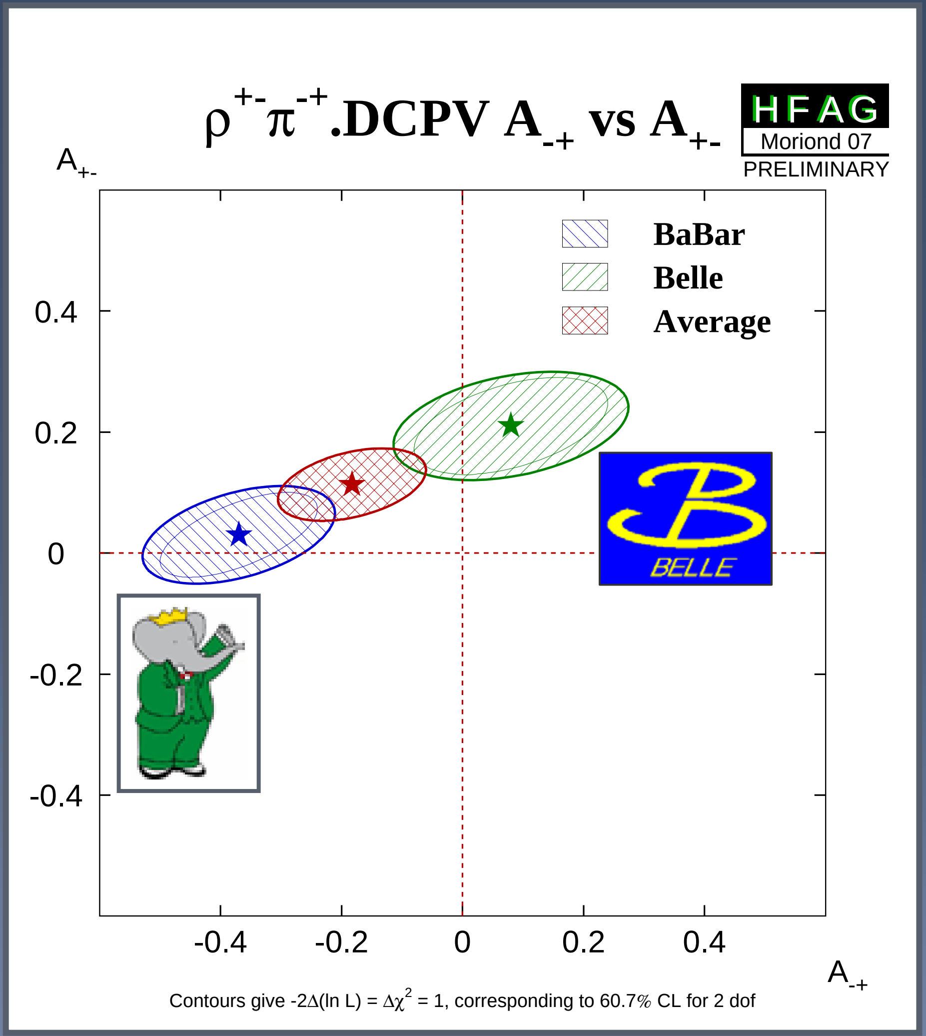


BaBar 375MBB

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

ϕ_2 (α)

– $B^0 \rightarrow \rho^{+-}\pi^{-+}$ Direct *CP* Violation



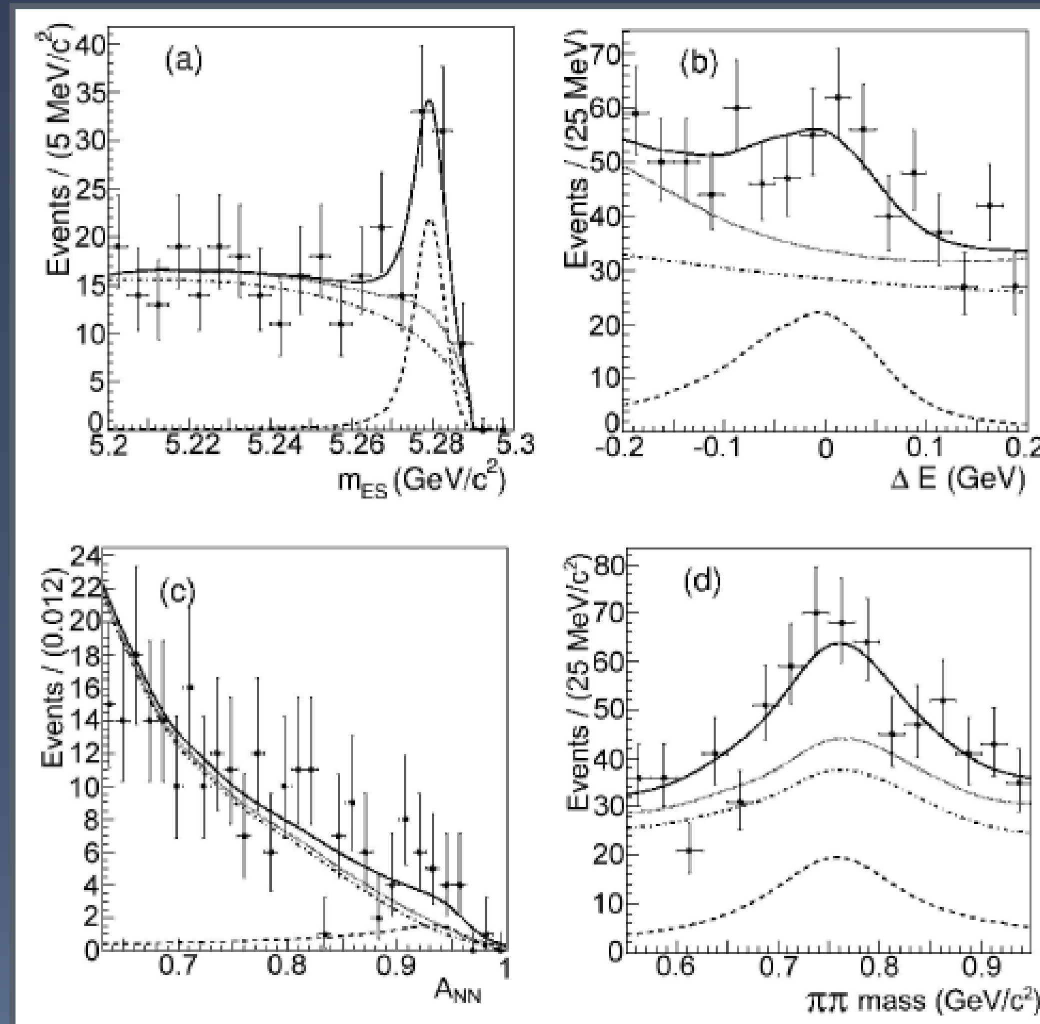
Belle: 2.3σ

Babar: <3.0σ

Average: ~3.0σ

$\phi_2\ (\alpha)$

– $B^+ \rightarrow \rho^+ \pi^0$



hep-ex/0701035

BaBar 232MBB

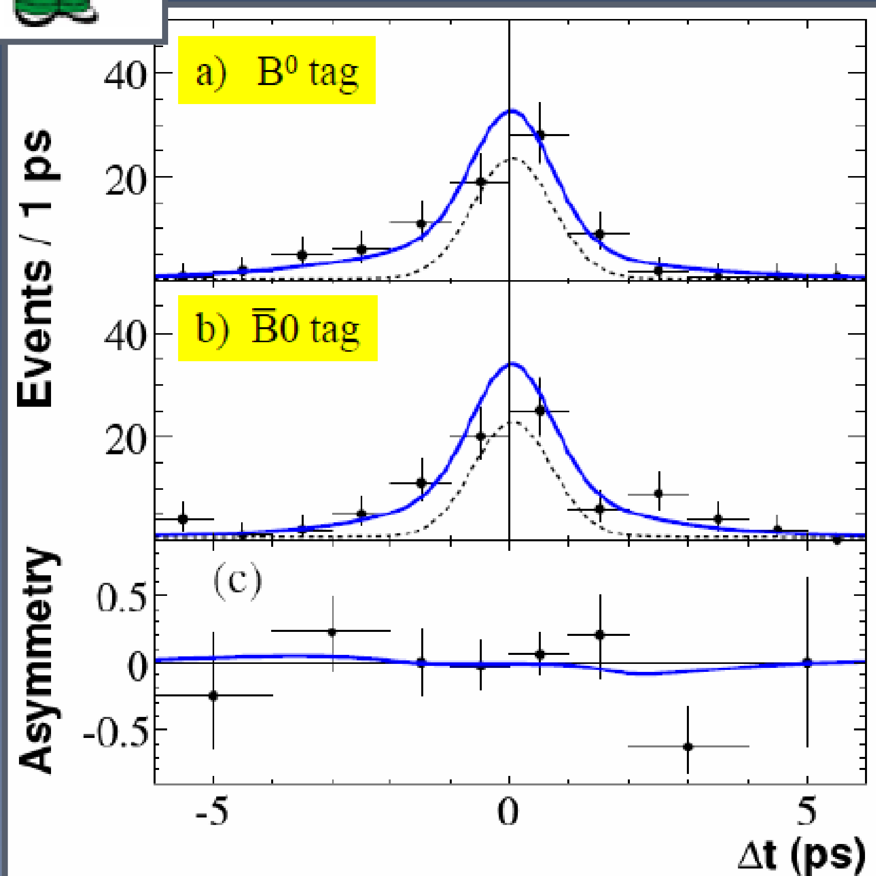
$Br = 10.2 \pm 1.4 \pm 0.9$

$A_{CP} = -0.01 \pm 0.13 \pm 0.02$

ϕ_2 (α)

– $B^0 \rightarrow a_1^{+-}\pi^{-+}$

hep-ex/0612050



BaBar 384MBB

$A_{CP} = -0.07 \pm 0.07 \pm 0.02$

$S = +0.37 \pm 0.21 \pm 0.07$

$C = -0.10 \pm 0.15 \pm 0.09$

$\Delta S = -0.14 \pm 0.21 \pm 0.06$

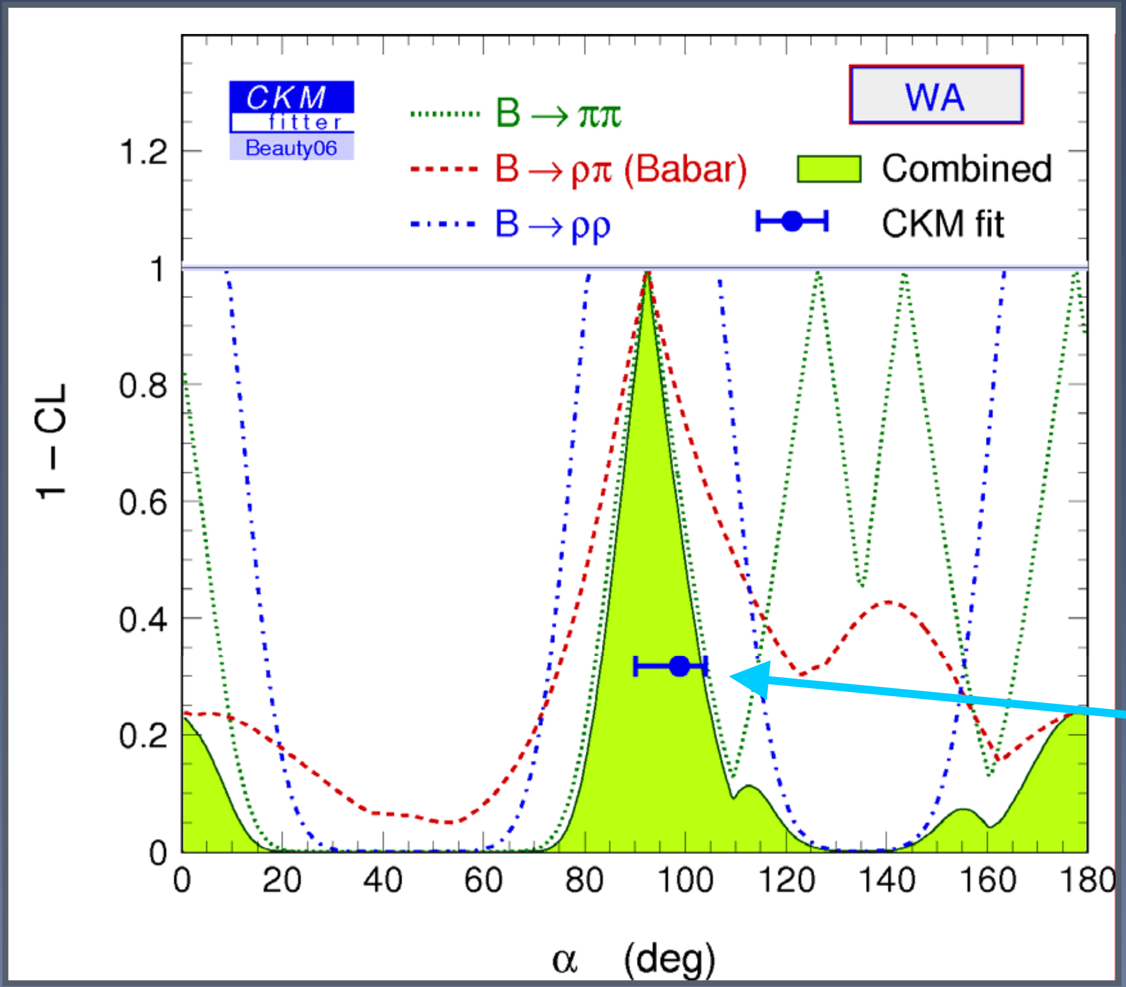
$\Delta C = +0.26 \pm 0.15 \pm 0.07$

$\phi_2^{eff} = (78.6 \pm 7.3)^\circ$ [stat. and syst.]

Can be used to constrain ϕ_2

Gronau, Zupan, PRD 73 (2006) 057502

ϕ_2 (α) – W/A



$$\phi_2 = 93.5^{+10.8}_{-9.6}$$

w/o Belle $B^0 \to (\rho\pi)^0$

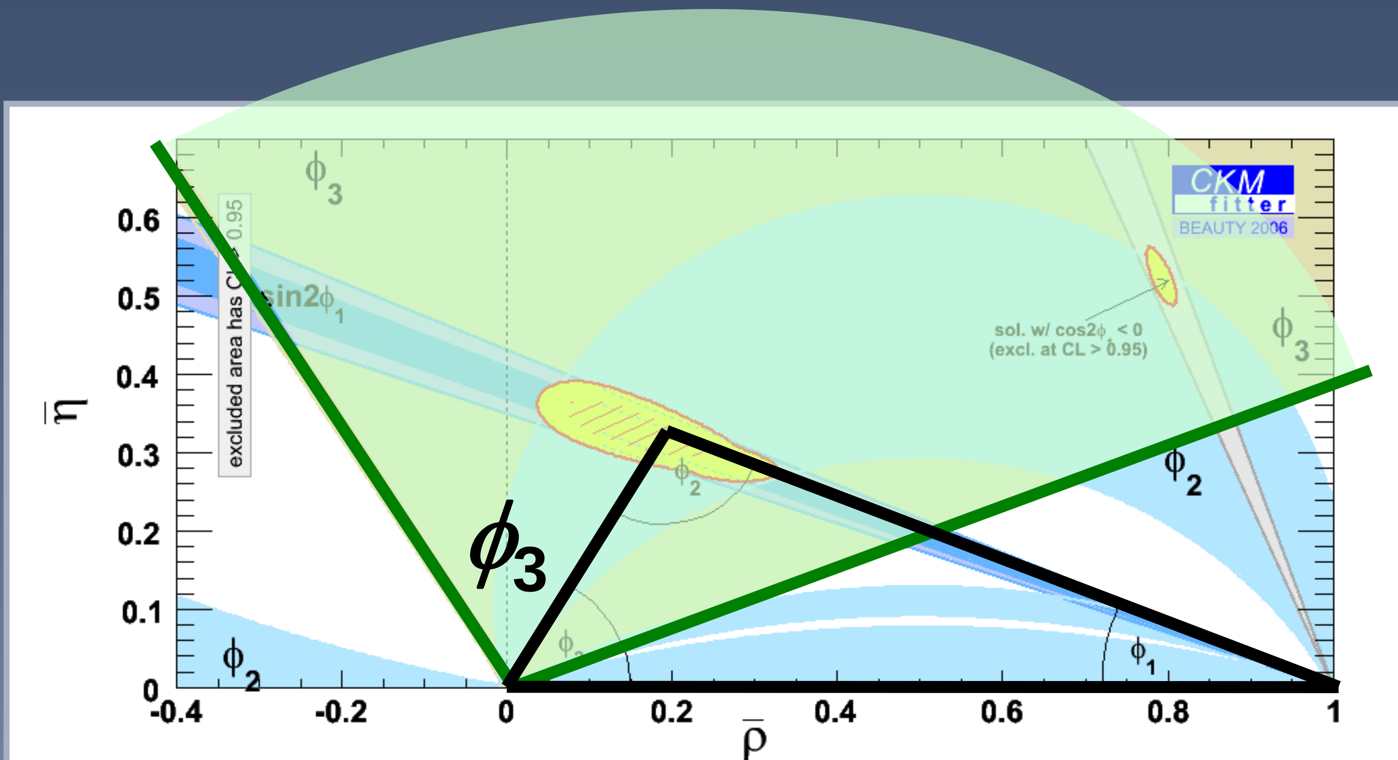
Consistent w/ SM expectation

ϕ_2 (α) – Revenge of the Theory(?)

- There are activities to limit ϕ_2 using $B^0 \to \rho^+\rho^-$, $\rho^{+-}\pi^{-+}$, $a_1{}^{+-}\pi^{-+}$, $(\pi^+\pi^-)$ with mild assumptions (broken $SU(3)$, P/T, …)
  - Gronau, Zupan, PRD 70 (2004) 074031
  - Gronau, Lunghi, Wyler, PLB 606 (2005) 95-102
  - Beneke, Gronau, Rohrer, Spranger PLB 638 (2006) 68-73
  - Gronau, Zupan, PRD 73 (2006) 057502

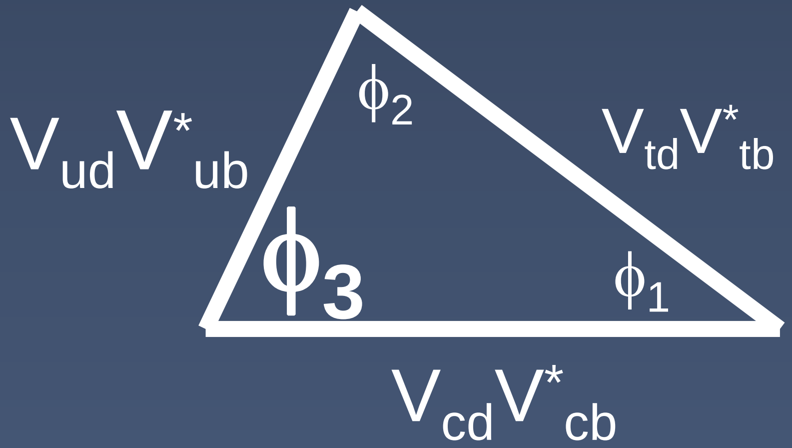
etc., etc… (sorry for those which are missing)

ϕ_3 (γ)



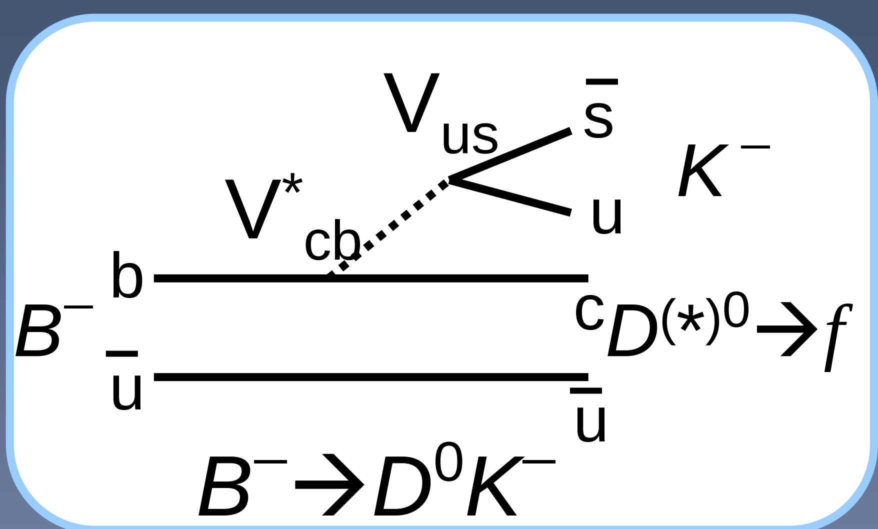
CKM fitter
BEAUTY 2006
excluded area has CL > 0.95
sin2ϕ_1
sol. w/ cos2ϕ_1 < 0
(excl. at CL > 0.95)
ϕ_3
ϕ_2
ϕ_1
$\bar{\eta}$
$\bar{\rho}$

ϕ_3 (γ) – How to Measure?

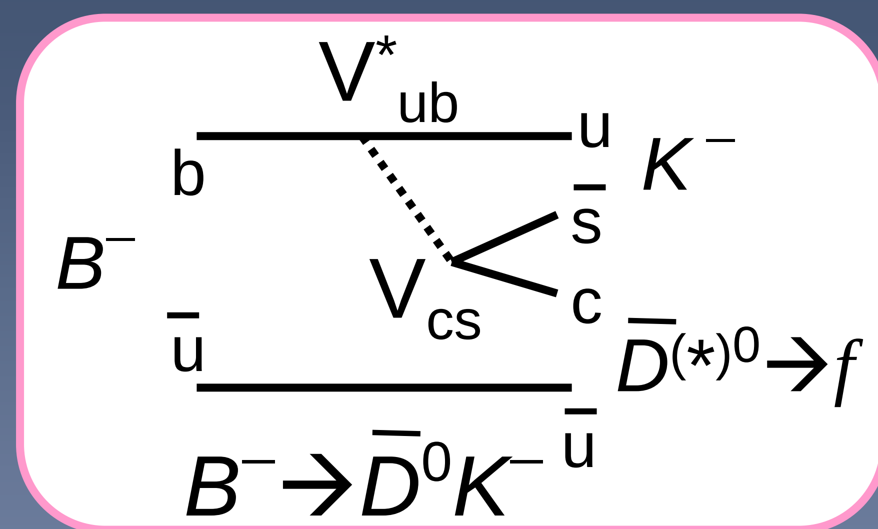


Color Suppression Factor

$$r_B \equiv \left| \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|$$

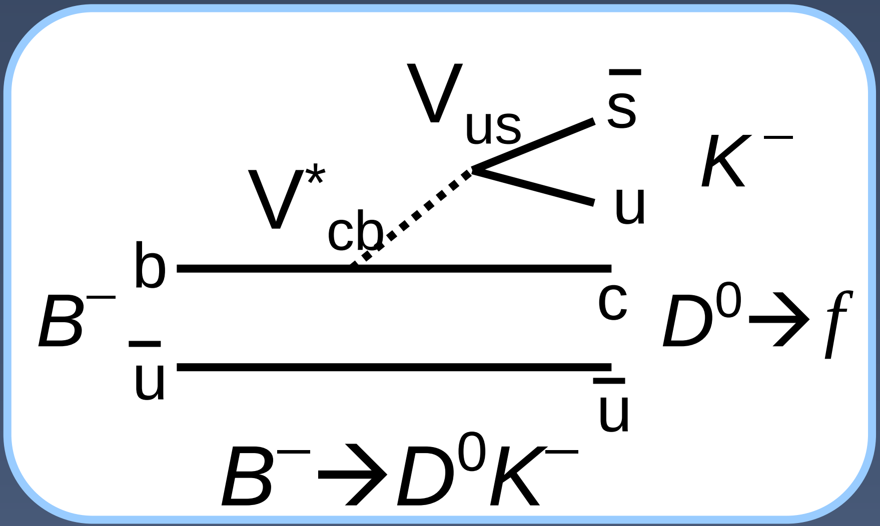


Color Allowed Decay

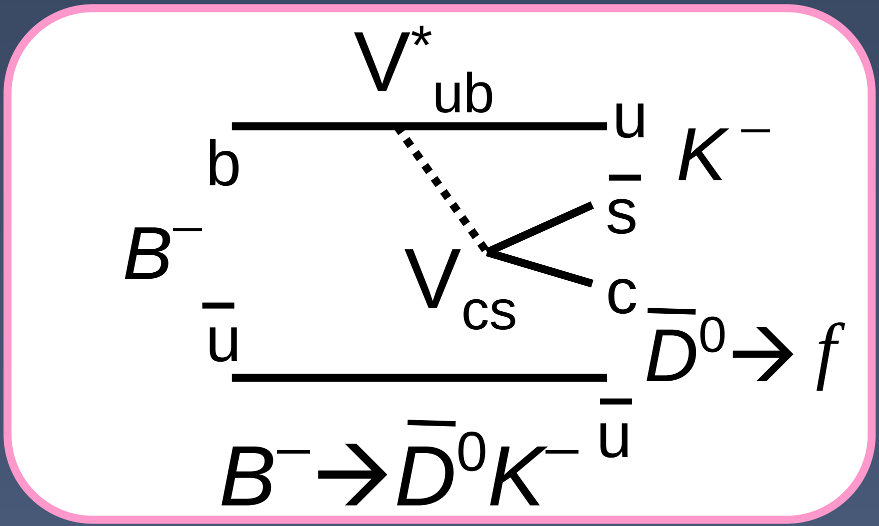


Color Suppressed Decay

ϕ_3 (γ) – How to Measure?



Color Allowed Decay



Color Suppressed Decay

Three Types of the Common Final State f

Dalitz: $f = K_S\pi^+\pi^-$

GLW: $f = D_{CP}$ [K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$, $K_S\omega$, $K_S\phi$, etc…]

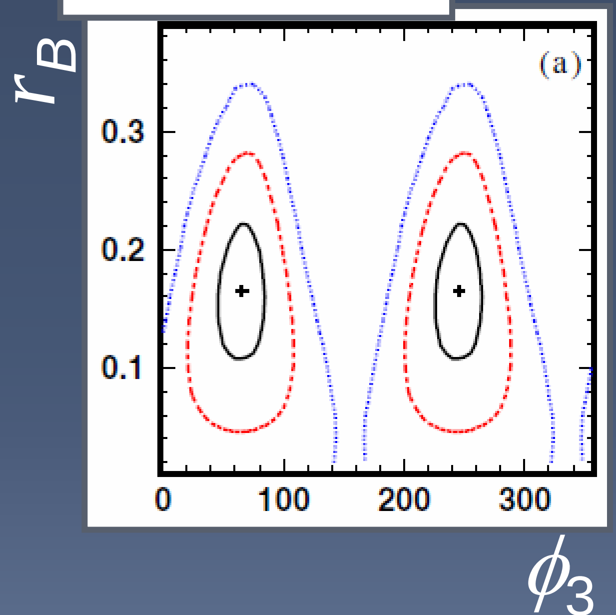
ADS: $f = D_{ADS}$ [$K^+\pi^-$], Suppressed Decays

ϕ_3 (γ) – Dalitz

Belle 388MBB

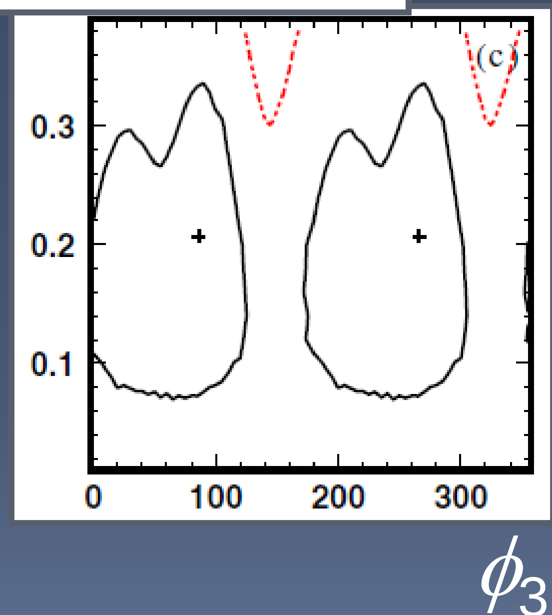
PRD73, 112009 (2006)

$B^\pm \to DK^\pm$



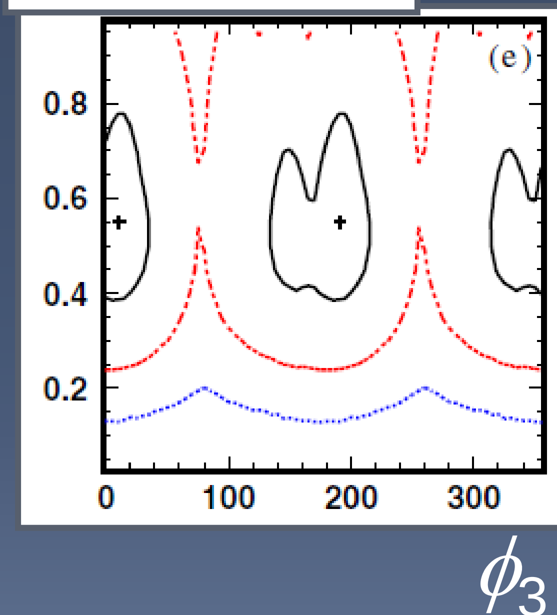
$\phi_3 = 66^{+19}_{-20}$ (stat.)

$B^\pm \to D^* K^\pm$



$\phi_3 = 86^{+37}_{-93}$ (stat.)

$B^\pm \to DK^{*\pm}$



$\phi_3 = 11^{+23}_{-57}$ (stat.)

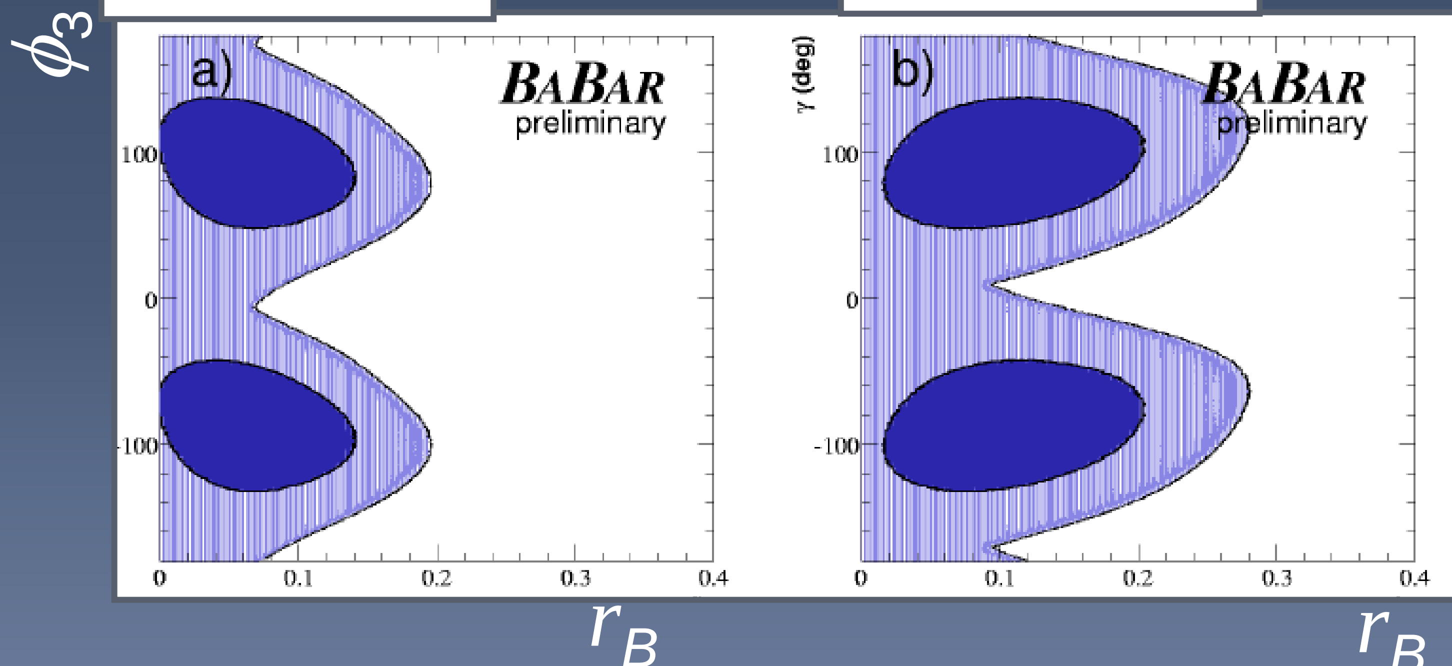
3 modes combined: $\phi_3 = 53^{+15}_{-18}$ (stat.) ± 3 (syst.) ± 9 (model)

ϕ_3 (γ) – Dalitz

BaBar 347MBB

hep-ex/0607104

$B^{\pm} \to DK^{\pm}$ $\qquad$ $B^{\pm} \to D^{*}K^{\pm}$



2 modes combined: $\phi_3 = 92 \pm 41(\text{stat.}) \pm 11(\text{syst.}) \pm 12(\text{model})$

ϕ_3 (γ) – Dalitz ($D^0 \rightarrow \pi^+\pi^-\pi^0$)

$324\times10^6\, B\bar{B}$ pairs

First measurement of CP parameters with this channel

$$|A^{\pm}(s^+,s^-)|^2 = |f_D(s^+,s^-) + r_B e^{i(\delta\pm\gamma)} f_D(s^-,s^+)|^2$$

$B^{\pm}\rightarrow D_{\pi\pi\pi 0}K^{\pm}$ amplitude — $\bar{D}^0\rightarrow\pi\pi\pi^0$ amplitude — $D^0\rightarrow\pi\pi\pi^0$ amplitude

$$r_B e^{i(\delta\pm\gamma)} = x_{\pm} + y_{\pm}$$

Polar coordinates

$$\rho_{\pm} \equiv \sqrt{\left(x_{\pm}-x^0\right)^2 + y_{\pm}^{\ 2}} \qquad \theta_{\pm} \equiv \tan^{-1}\left(\frac{y_{\pm}}{x_{\pm}-x^0}\right)$$

$$x^0 = \int f_D(s^+,s^-)^* f_D(s^-,s^+)\, ds^- ds^+ = 0.85$$

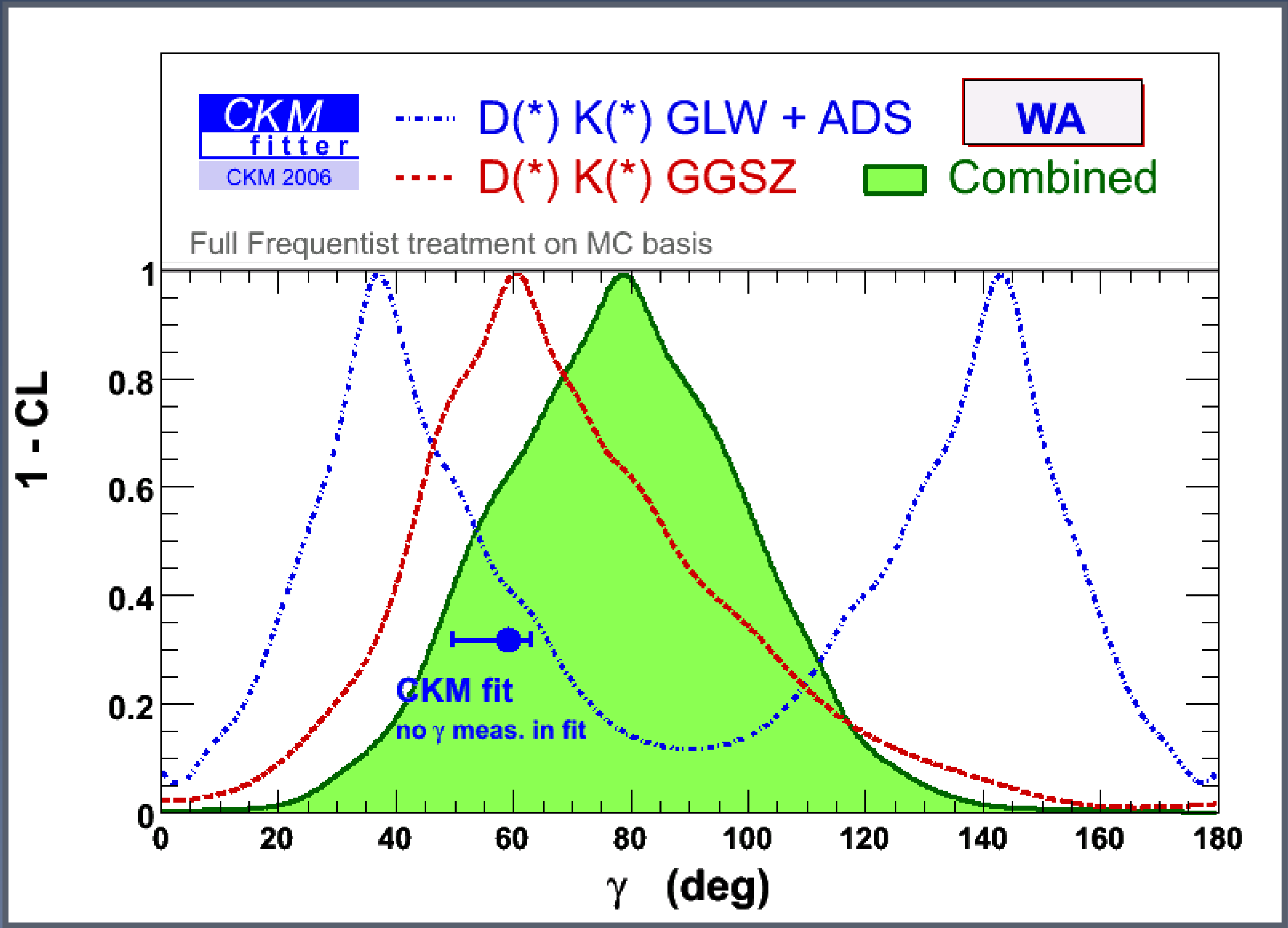
$N_{sig}=170\pm29$

$$\rho_- = 0.72\pm0.11\pm0.06, \quad \theta_- = (173\pm42\pm17)^{\circ}$$
$$\rho_+ = 0.75\pm0.11\pm0.06, \quad \theta_+ = (147\pm23\pm12)^{\circ}$$

Effect on γ not evaluated yet

from V. Lombardo's talk in Lake Louise 2007

ϕ_3 (γ) – W/A



$$\phi_3 = 77 \pm 31$$

Summary

- ϕ_2 (α)
  - Progress in experimental measurements (from last summer)
    - **New:** $B^0 \to \rho^+\rho^-$ (Belle), $B^0 \to \pi^+\pi^-$, $K^+\pi^-$ (BaBar)
    - **Submitted:** $B^0 \to \pi^+\pi^-$ (Belle), $B^0 \to \rho\pi$ (BaBar, Belle), $B^0 \to \rho^0\rho^0$ (BaBar), $B^0 \to a_1\pi$ (BaBar), $B^+ \to \rho^{+-}\pi^0$ (BaBar)
    - **Published:** $B^0 \to h^+h^-$ (BaBar)
  - Interesting activities in the theory side
- ϕ_3 (γ)
  - Progress (from last summer)
    - **New:** $B^+ \to D^0K^+$ ($D^0 \to \pi^+\pi^-\pi^0$)

ϕ_3 (γ) – GLW

M.Gronau and D. London, PLB **253**, 483 (1991)
M. Gronau and D. Wyler, PLB **265**, 172 (1991)

CP-even : $D_+ \to K^+K^-, \pi^+\pi^-$
CP-odd : $D_- \to K_S\pi^0, K_S\omega, K_S\phi$ …

CP Asymmetry

$$\mathcal{A}_\pm = \frac{Br(B^- \to D_\pm K^-) - Br(B^+ \to D_\pm K^+)}{Br(B^- \to D_\pm K^-) + Br(B^+ \to D_\pm K^+)} = \frac{\pm 2r_B \sin\delta \sin\phi_3}{1 + r_B{}^2 \pm 2r_B \cos\delta\cos\phi_3}$$

Non-zero CPV required for ϕ_3 constraint

Additional Constraint

$$\mathcal{R}_\pm = \frac{Br(B \to D_\pm K)/Br(B \to D_\pm \pi)}{Br(B \to D^0 K)/Br(B \to D^0\pi)} = 1 + r_B{}^2 \pm 2r_B\cos\delta\cos\phi_3$$

3 Observables vs. 3 Unknowns (r_B, δ, ϕ_3)

High precision (little theory uncertainty) at high statistics
Can be used to improve the constraint of Dalitz plot at current statistics

ϕ_3 (γ) – GLW

Belle 275MBB

D_{CP} decays

$\mathcal{A}_+ = +0.06 \pm 0.14 \pm 0.05$

$\mathcal{A}_- = -0.12 \pm 0.14 \pm 0.05$

$\mathcal{R}_+ = 1.13 \pm 0.16 \pm 0.05$

$\mathcal{R}_- = 1.17 \pm 0.14 \pm 0.05$

D^*_{CP} decays

$\mathcal{A}_+ = -0.2 \pm 0.22 \pm 0.04$

$\mathcal{A}_- = +0.13 \pm 0.3 \pm 0.08$

$\mathcal{R}_+ = 1.41 \pm 0.25 \pm 0.06$

$\mathcal{R}_- = 1.15 \pm 0.31 \pm 0.12$

PRD(RC) 73, 051106 (2006)

BaBar 232MBB

$D_{CP} K$ decays

$\mathcal{A}_+ = +0.35 \pm 0.13 \pm 0.04$

$\mathcal{A}_- = -0.06 \pm 0.13 \pm 0.03$

$\mathcal{R}_+ = 0.90 \pm 0.12 \pm 0.04$

$\mathcal{R}_- = 0.86 \pm 0.10 \pm 0.05$

$D_{CP} K^*$ decays

$\mathcal{A}_+ = -0.08 \pm 0.19 \pm 0.08$

$\mathcal{A}_- = -0.26 \pm 0.40 \pm 0.12$

$\mathcal{R}_+ = 1.96 \pm 0.40 \pm 0.11$

$\mathcal{R}_- = 0.65 \pm 0.26 \pm 0.08$

PRD(RC)73, 051105 (2006)
PRD(RC)72, 071103 (2005)

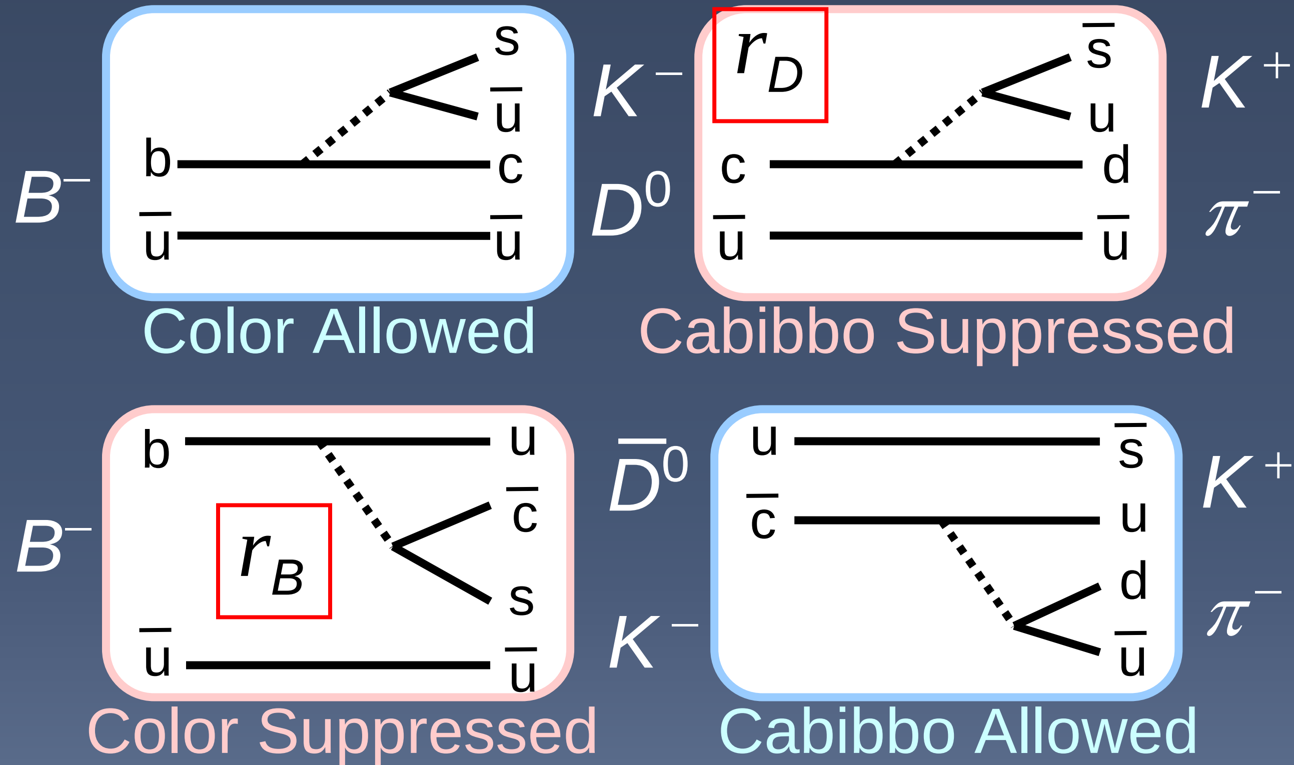
D. Atwood, I. Dunietz and A. Soni, PRL **78**, 3357 (1997)
PRD **63**, 036005 (2001)

ϕ_3 (γ) – ADS

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

$B^- \to D^0 K^-$
$\quad \hookrightarrow K^+ \pi^-$

$B^- \to \overline{D}^0 K^-$
$\quad \hookrightarrow K^+ \pi^-$



$$\mathcal{R}_{DK} = \frac{Br(B \to D_{\mathrm{ADS}} K)}{Br(B \to D_{\mathrm{fav}} K)} = r_B^2 + r_D^2 + 2 r_B r_D \cos\phi_3 \cos\delta$$

High precision (little theory uncertainty) at high statistics
Can be used to improve the constraint of Dalitz plot at current statistics

ϕ_3 (γ) – ADS

PRD(RC) 071104 (2005)

BaBar 232MBB

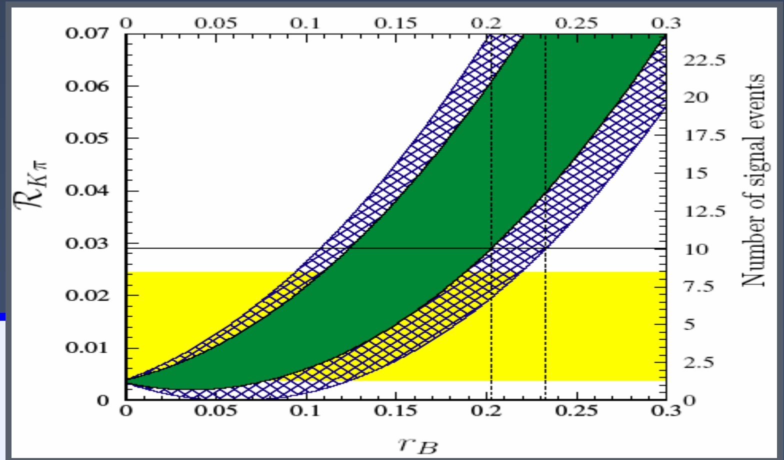
$$\mathcal{R}_{DK} = 13^{+11}_{-9} \times 10^{-3}$$

$$\mathcal{R}_{D^*[D\pi^0]K} = -2^{+10}_{-6} \times 10^{-3}$$

$$\mathcal{R}_{D^*[D\gamma]K} = 11^{+18}_{-13} \times 10^{-3}$$

r_B<0.23 (90% CL) for $B \to DK$

r_B<0.16 for $B \to D^*K$

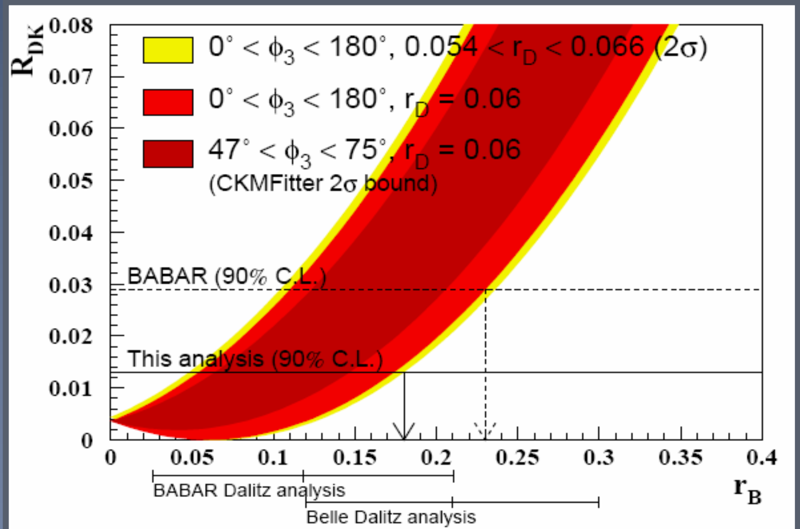


Belle 275MBB

$$\mathcal{R}_{DK} = (0.0^{+8.4}_{-7.9} \pm 1.0) \times 10^{-3}$$

$$< 0.014 \text{ (at 90\% C.L.)}$$

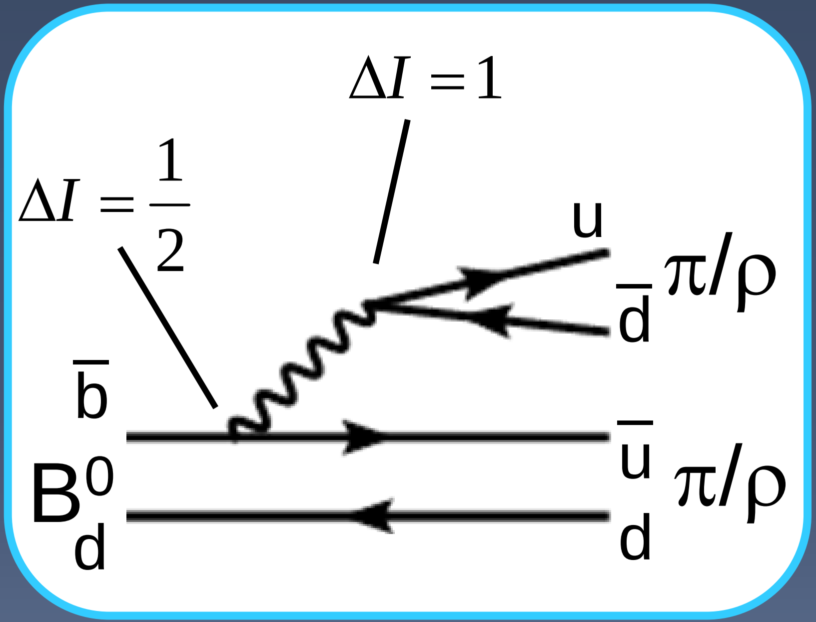
r_B < 0.18 (at 90% C.L.)



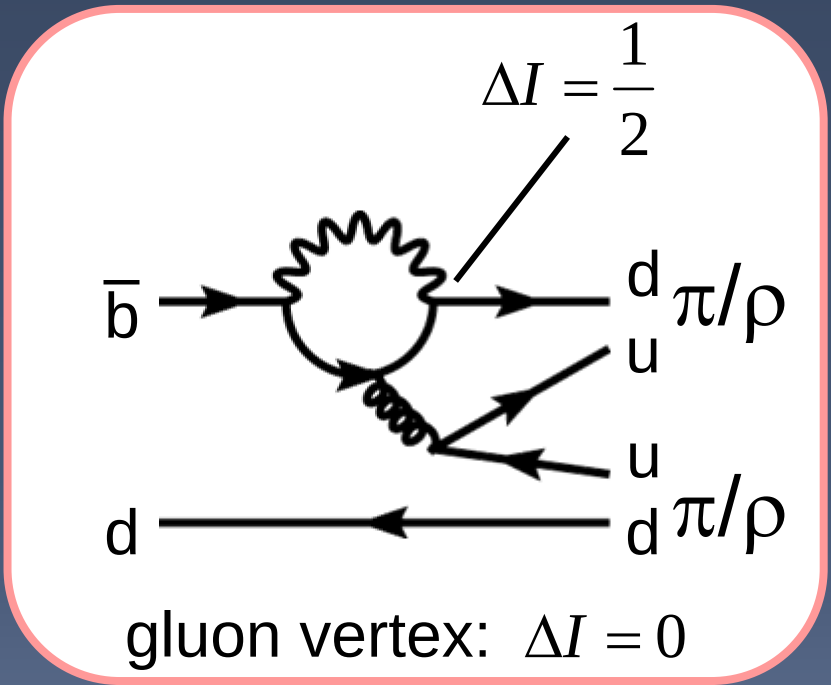
hep-ex/0508048

Gronau & London (1990)

ϕ_2 (α) – Isospin Relations



Tree Diagram: ΔI=1/2 or 3/2



Gluon Penguin: ΔI=1/2

Initial state = B^0: I = 1/2

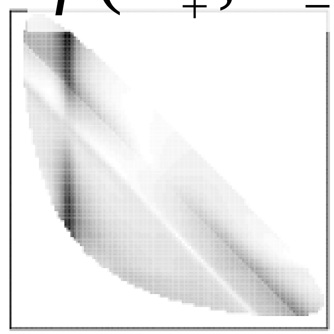
Final state = $\pi\pi$: I = 0, 1, 2

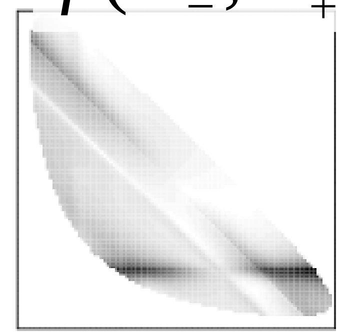
Gluon penguin does not contribute to this component.

A.Bondar, Proceedings of the Belle Workshop, September (2002)
A.Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD 68, 054018 (2003)

ϕ_3 (γ) – Dalitz

$$\left|A(m_+^2, m_-^2)\right|^2 = \Big|\, f(m_+^2, m_-^2) + re^{i\delta \pm i\phi_3} f(m_-^2, m_+^2) \,\Big|^2$$





$$A(B^+ \to DK^+) = A(B^+ \to \overline{D}^0 K^+) + r_B e^{i\delta + i\phi_3} A(B^+ \to D^0 K^+)$$

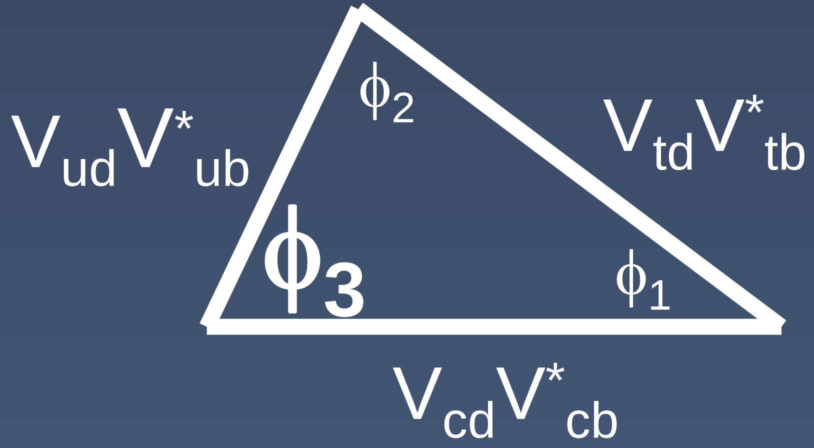
$$A(B^- \to DK^-) = A(B^- \to D^0 K^-) + r_B e^{i\delta - i\phi_3} A(B^- \to \overline{D}^0 K^-)$$

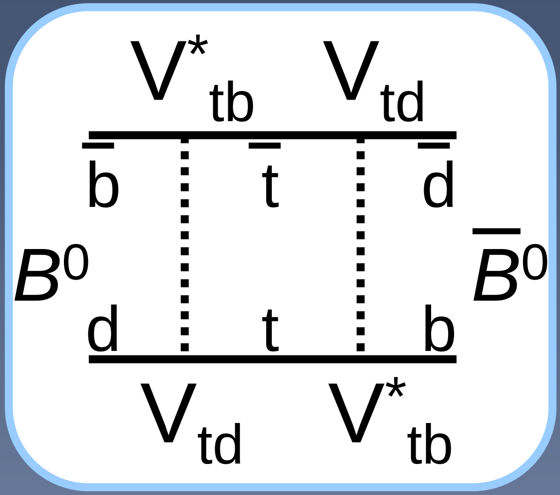
CP-violating interference in Dalitz plot → ϕ_3

(r_B, δ): Strong interaction parameters important for ϕ_3 measurement

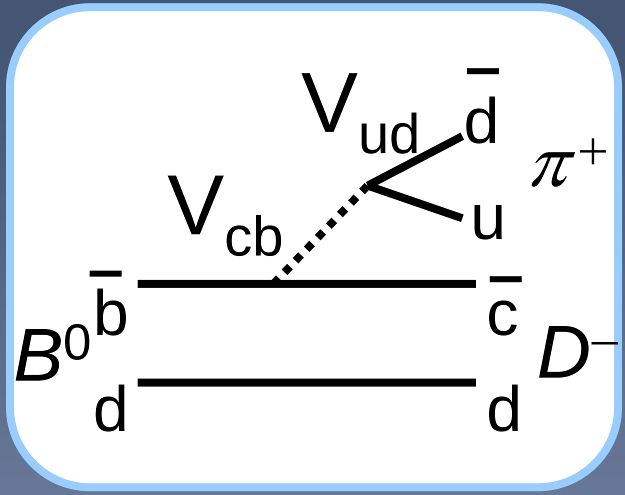
Small r_B → Weak ϕ_3 constraint

$\sin[2\phi_1+\phi_3$ (or $2\beta+\gamma$)] – How to Measure?

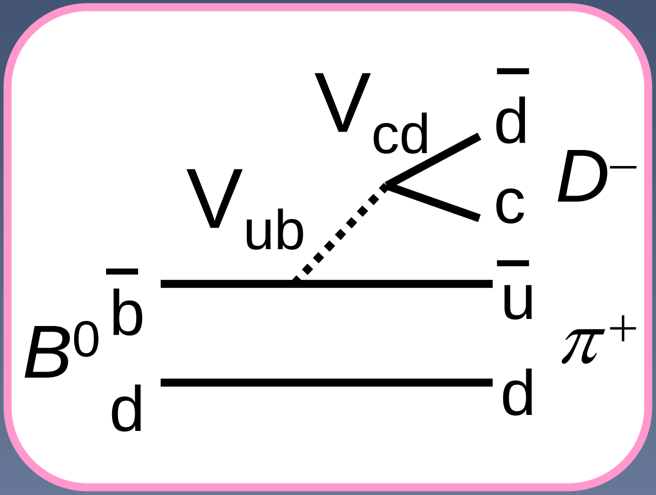




Mixing



Cabibbo Allowed



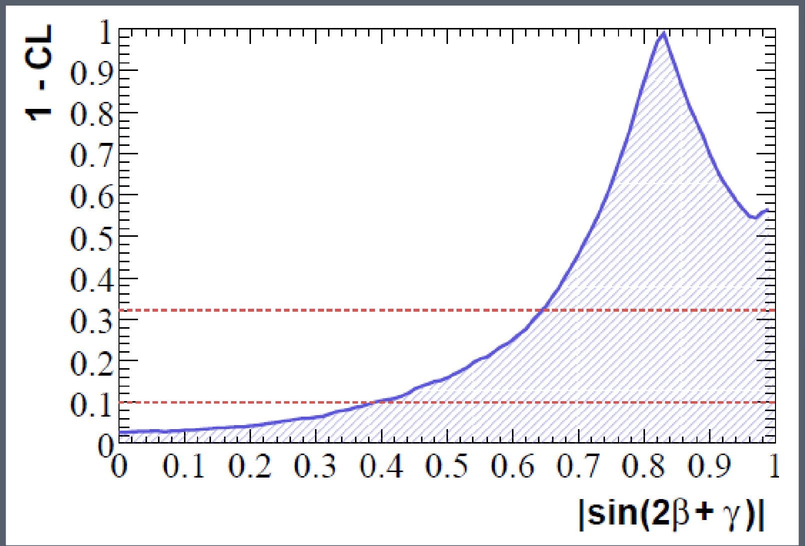
Doubly Cabibbo Suppressed

$\sin[2\phi_1+\phi_3$ (or $2\beta+\gamma$)] – $B^0 \rightarrow D^{(*)}\pi$

BaBar 232MBB

$|\sin(2\phi_1+\phi_3)| > 0.64$ (0.40) at 68% (90%) C.L.

PRD 71 (2005) 112003
PRD 73 (2006) 111101



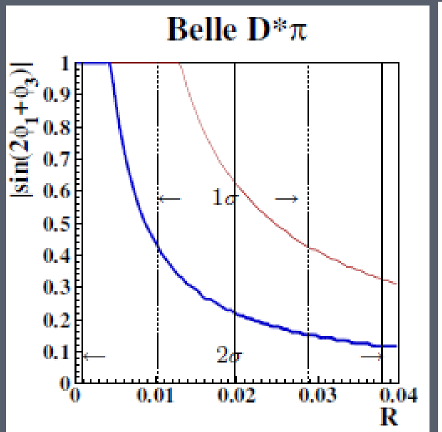
Belle 386MBB

$D^*\pi$
$|\sin(2\phi_1+\phi_3)| > 0.44$ (0.13)

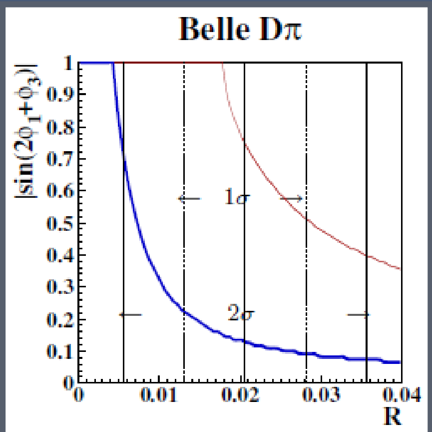
$D\pi$
$|\sin(2\phi_1+\phi_3)| > 0.52$ (0.07)

at 68% (90%) C.L.

PRD 73 (2006) 092003

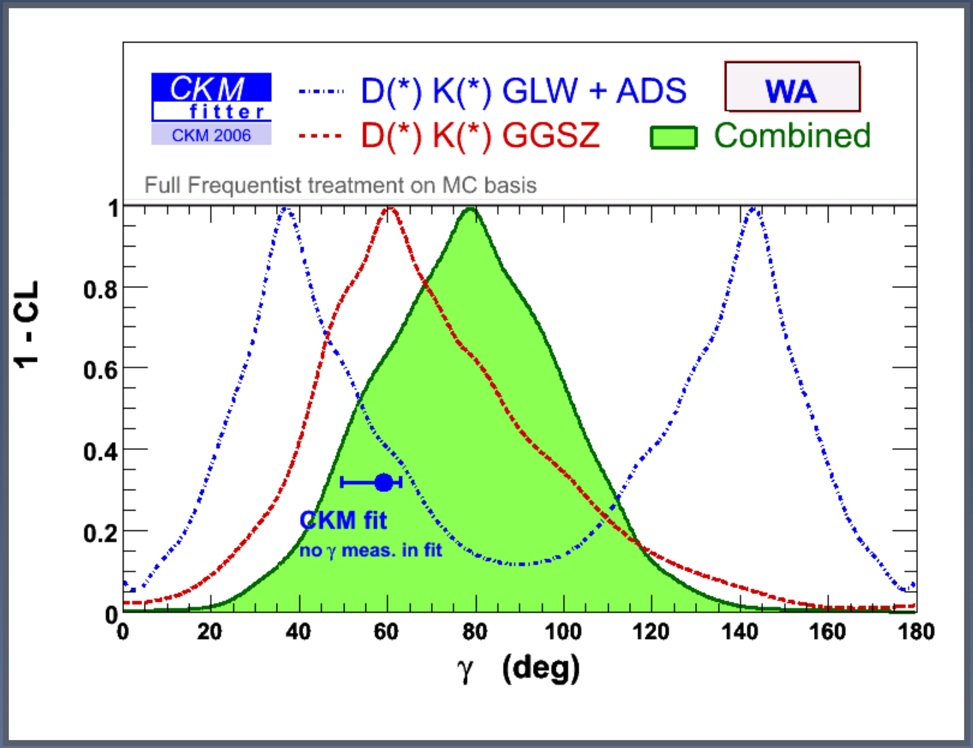


$|\sin(2\phi_1+\phi_3)| > 0.44(0.13)$
at 68% (95%)CL



$|\sin(2\phi_1+\phi_3)| > 0.52(0.07)$
at 68% (95%)CL

ϕ_3 (γ) – W/A



$$\phi_3 = 77 \pm 31$$

But there are discussions on the statistical treatment…

- Non-linearity due to the dependence on r_B
- Different way in the assignment of syst. errors (final or intermediate)
- and more…