Angles of the CKM unitarity triangle measured at Belle

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Les Rencontres de Physique de la Vallee D'Aoste
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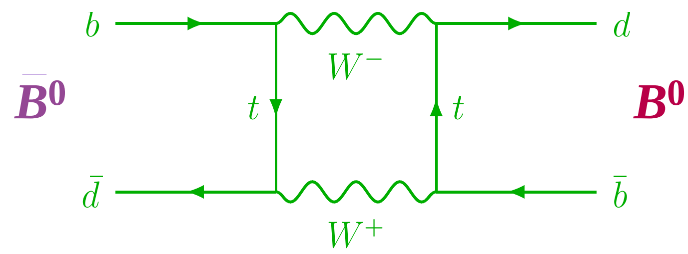
- **Introduction**
- **Determining sin(2ϕ_1) (β)**
- **Determining sin(2ϕ_2) (α)**
- **Determining ϕ_3 (γ)**
- **Summary**

Introduction

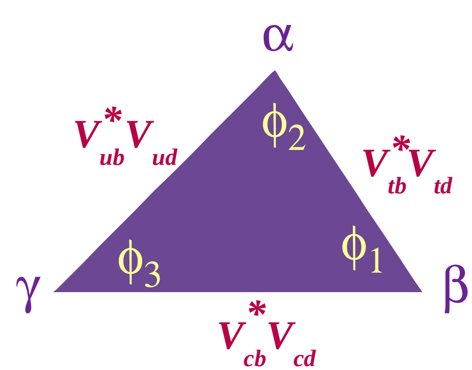
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$
$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$



$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}} \approx \sqrt{\frac{M_{12}^*}{M_{12}}} = e^{i2\phi_1} \qquad \text{(phase of } V_{td}^* V_{tb}\text{)}$$

$$\frac{N_{\overline{B}^0\to f} - N_{B^0\to f}}{N_{\overline{B}^0\to f} + N_{B^0\to f}} = \mathcal{A}_f \cos(\Delta m\,\Delta t) + \mathcal{S}_f \sin(\Delta m\,\Delta t)$$

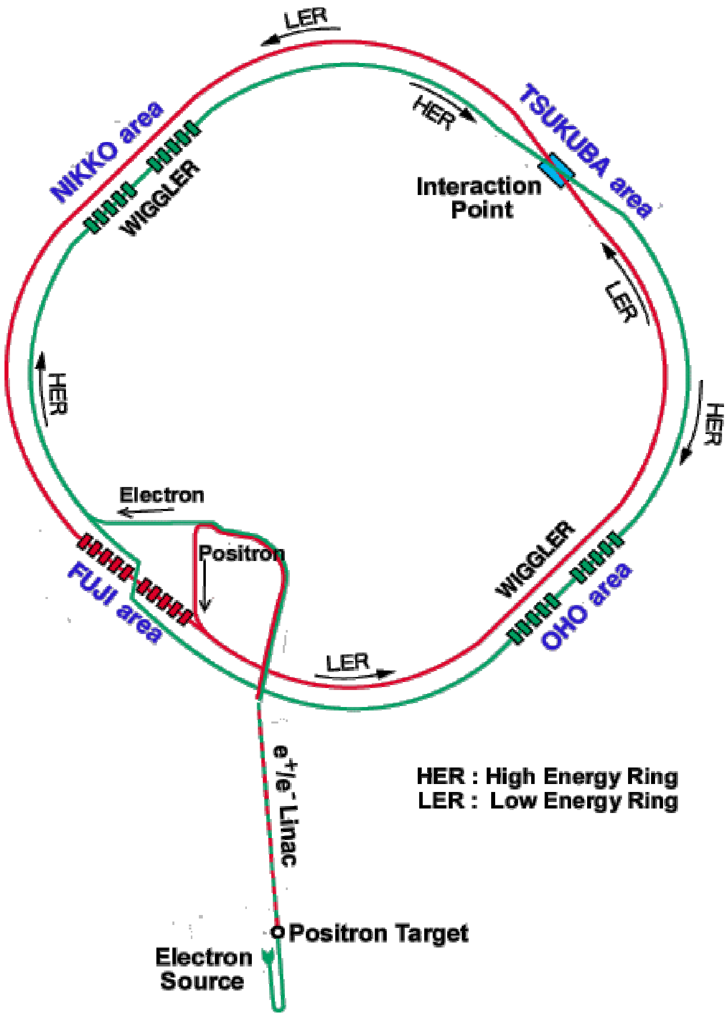
$$\mathcal{A}_f = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad \mathcal{S}_f = \frac{2Im\,\lambda}{1+|\lambda|^2}$$



$$\lambda_f = \left(\frac{q}{p}\right)\frac{A(\overline{B}^0\to f)}{A(B^0\to f)} = e^{i2\phi_1}\, e^{i2\phi} \qquad \text{(no penguin)}$$

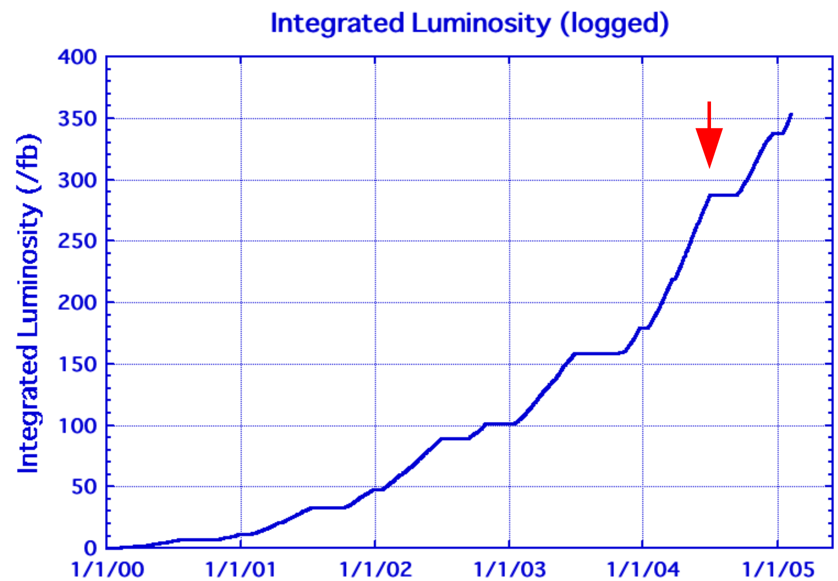
Note: $\mathcal{A}_f = -\mathcal{C}_f$

Belle at KEKB



$e^+e^- \to \Upsilon(4S) \to \bar{B}B$

3.5 GeV on 8.0 GeV



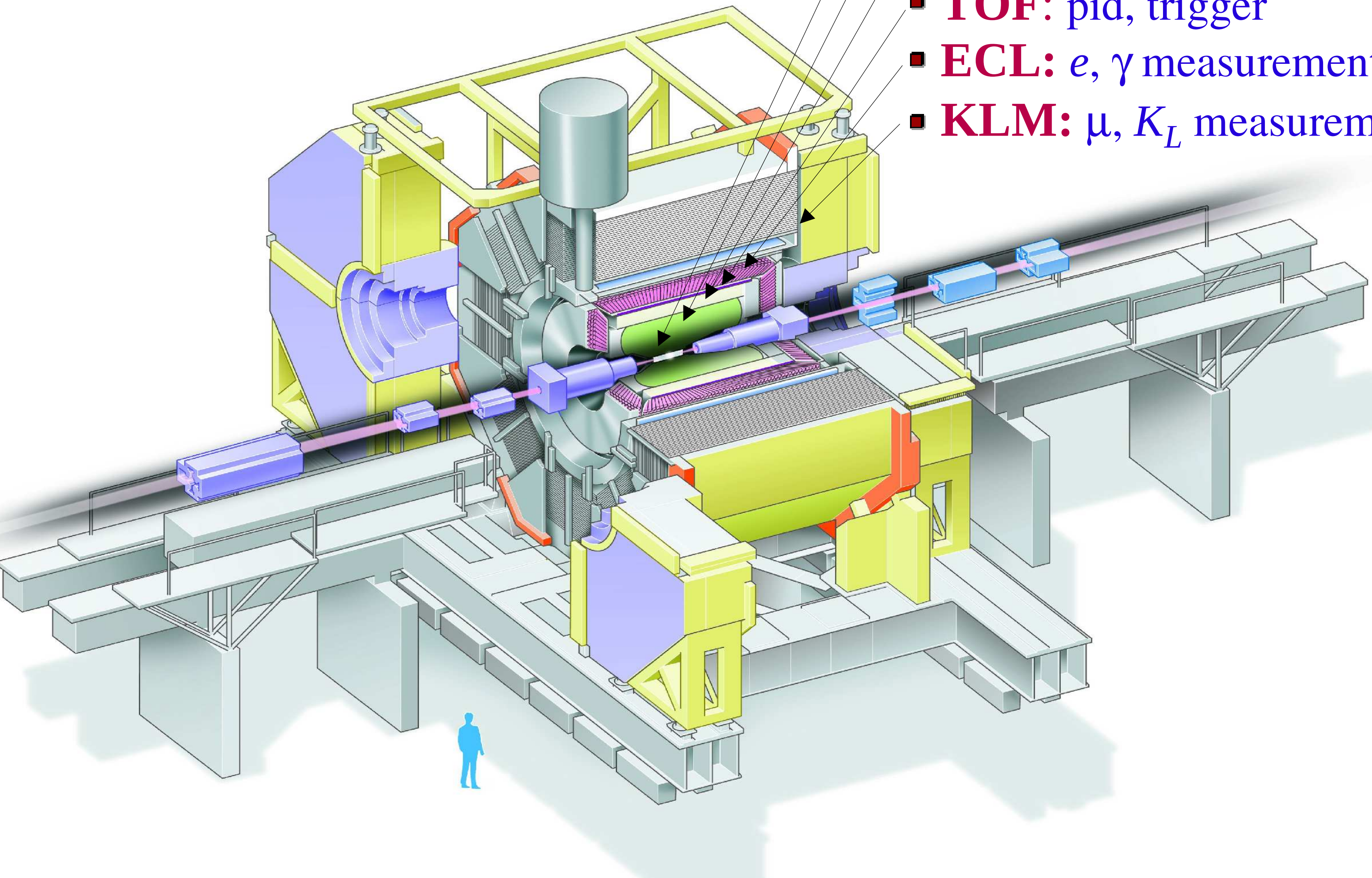
$\int L\,dt = 369\ fb^{-1}$ **on 28 Feb 2005**

L_{peak} (max) = $1.5 \times 10^{34}\ cm^{-2}\ s^{-1}$

253 fb^{-1} on resonance (275M BB)
by July 2004 **(results presented here)**

The Belle detector

- **SVD:** vertexing (lifetime)
- **CDC:** tracking, *dE/dx* for pid
- **ACC:** aerogel Cerenk. Counter
- **TOF**: pid, trigger
- **ECL:** *e*, γ measurement
- **KLM:** μ, K_L measurement



Analysis Overview

1) $B \to f$ selection:

$$m_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

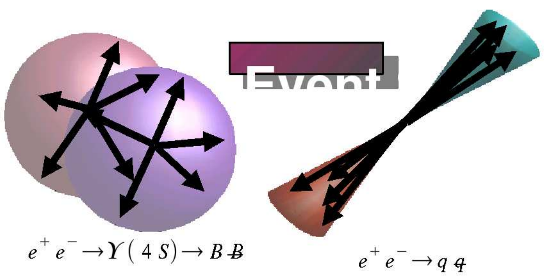
$$\Delta E = E^*_B - E^*_{beam}$$

(e.g., for $B \to \pi^+\pi^-$:
$5.271 < m_{bc} < 5.287$ GeV/c^2
$|\Delta E| < 0.064$ GeV)

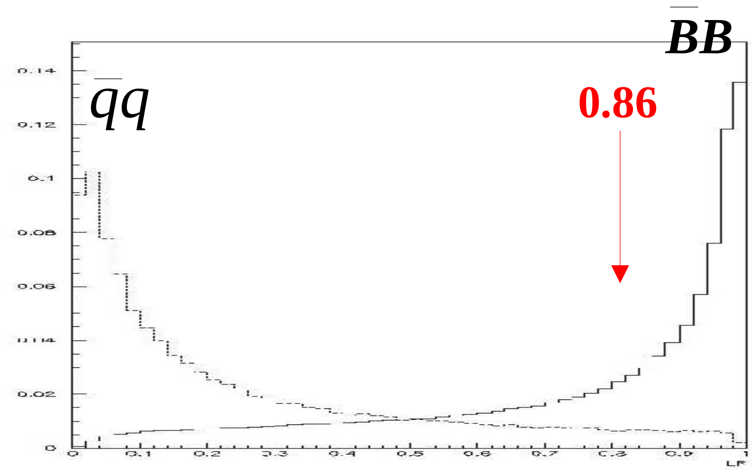
2) Flavor tagging:

mainly $K^\pm$, $\mu^\pm$, $e^\pm$ output: $q = \pm 1$, quality $r = 0$–1

3) Continuum suppression:



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



KLR

4) Vertexing and Δt fit

Measurement of $\sin(2\phi_1)$ with $B^0 \to J/\psi\, K^0$

$$\lambda = \sqrt{\frac{M_{12}^*}{M_{12}}}\,\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} = -\left(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\right)\left(\frac{V_{cb}\,V_{cs}^*}{V_{cb}^*\,V_{cs}}\right)\left(\frac{V_{cd}^*\,V_{cs}}{V_{cd}\,V_{cs}^*}\right)$$

$$= -\frac{V_{td}V_{tb}^*\,V_{cb}V_{cd}^*}{V_{td}^*V_{tb}\,V_{cb}^*V_{cd}}$$

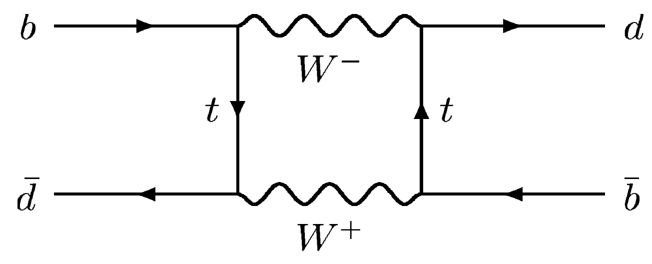
$$= -\frac{-V_{cb}V_{cd}^*/(V_{td}^*V_{tb})}{-V_{cb}^*V_{cd}/(V_{td}V_{tb}^*)}$$

$$= -\frac{|\mathcal{M}|e^{-i\phi_1}}{|\mathcal{M}|e^{i\phi_1}}$$

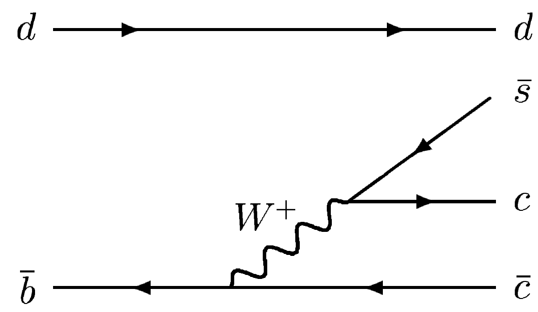
$$= -e^{-2i\phi_1}$$

$$\Rightarrow \quad \mathcal{A}_{(J/\psi\,K^0)} = 0 \qquad \mathcal{S}_{(J/\psi\,K^0)} = \sin(2\phi_1)$$

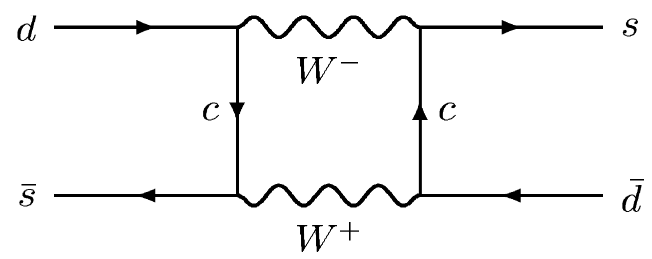
$\bar{B}^0$-B^0 oscillation:



Tree:

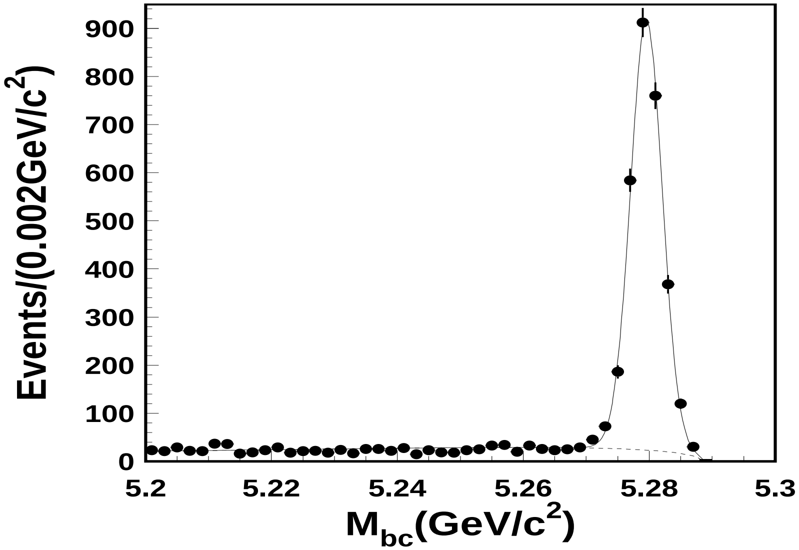


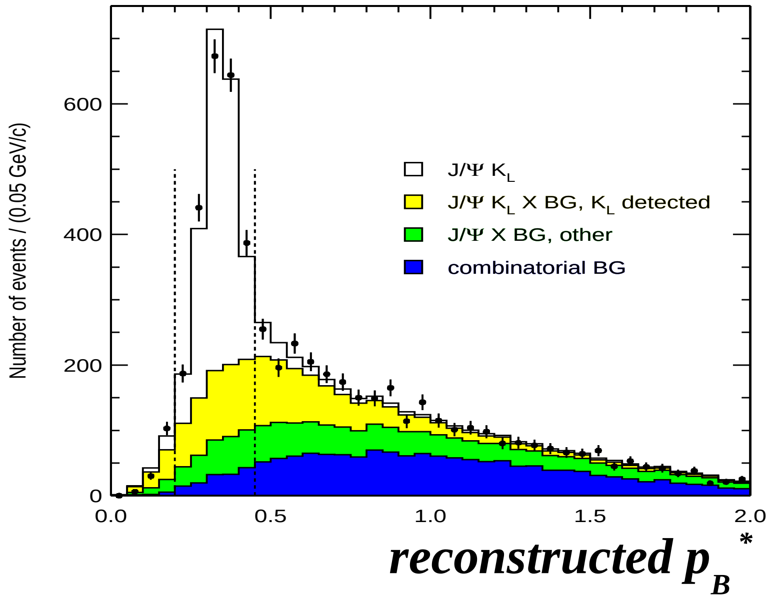
$\bar{K}^0$-K^0 oscillation:



Measurement of sin(2ϕ_1) with b→ccs (hep-ex/0408111)

140 fb $^{-1}$:





$B^0 \to J/\psi\, K_S$ (CP = –1)

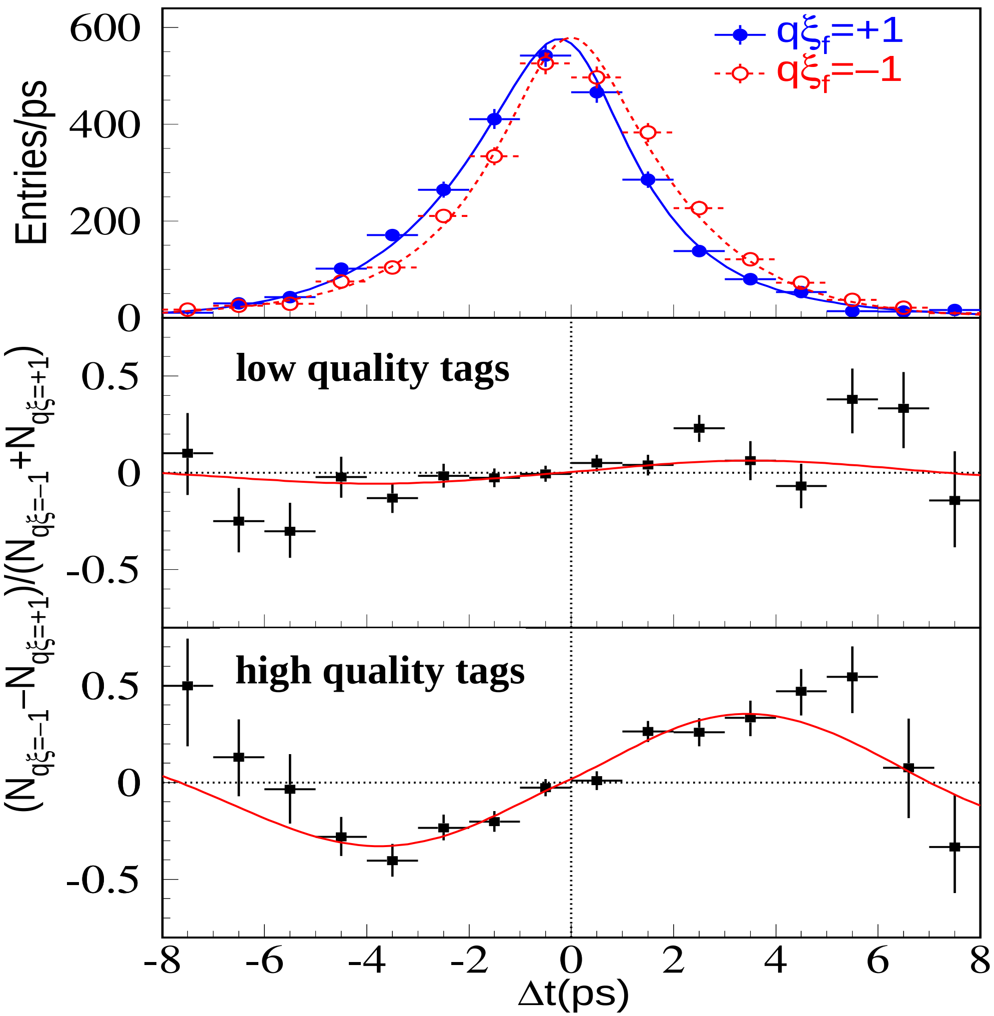
140 fb^{-1}: 2911 events
93% pure
253 fb^{-1}: 4150 events
96% pure

$B^0 \to J/\psi\, K_L$ (CP = +1)

140 fb^{-1}: 2322 events
63% pure

Note: cannot use ΔE because we don't have E_{KL}

Measurement of $\sin(2\phi_1)$ with $b\to ccs$ (hep-ex/0408111)



140 fb^{-1}:

$\sin(2\phi_1) = 0.728 \pm 0.056 \pm 0.023$

$|\lambda| = 1.007 \pm 0.041 \pm 0.023$

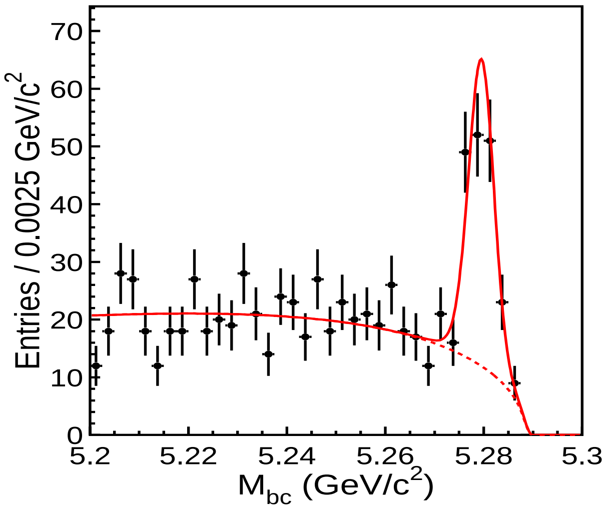
$\Rightarrow \quad \phi_1 = (23.3\ ^{+2.7}_{-2.4})^{o}$

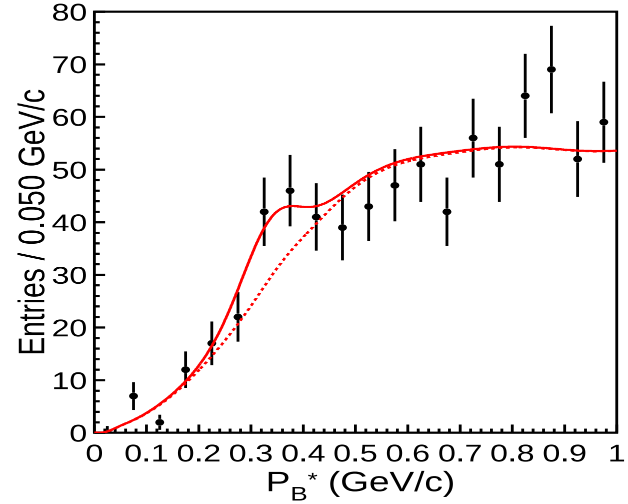
close to BaBar 210 fb^{-1}:

$\sin(2\phi_1) = 0.722 \pm 0.040 \pm 0.023$

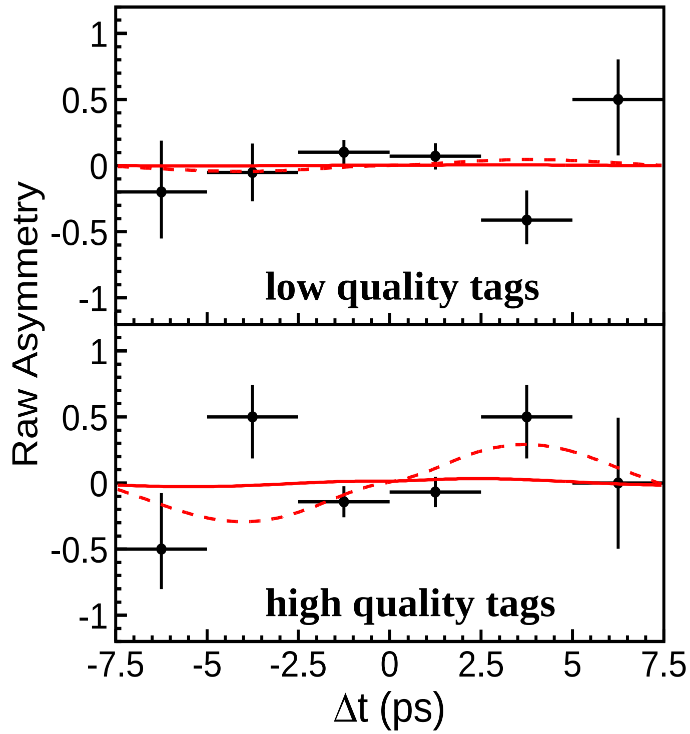
$|\lambda| = 0.950 \pm 0.031 \pm 0.013$

Measurement of $\sin(2\phi_1)$ *with* $b \to sss$ **(hep-ex/0409049)**





$B^0 \to \phi K^0$:



$B^0 \to \phi K_S$ ($CP = -1$)

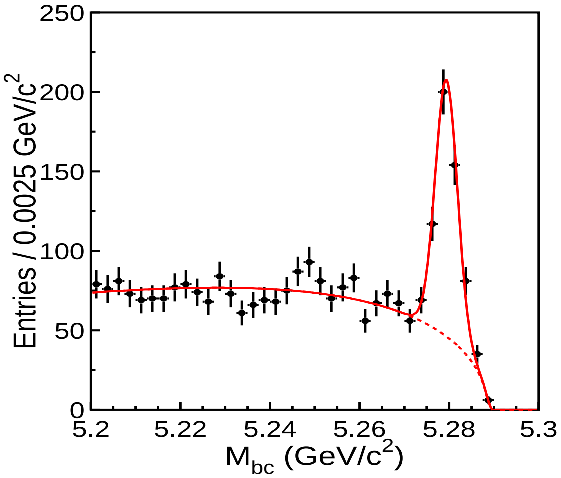
$N = 139 \pm 14$, 63% pure

$B^0 \to \phi K_L$ ($CP = +1$)

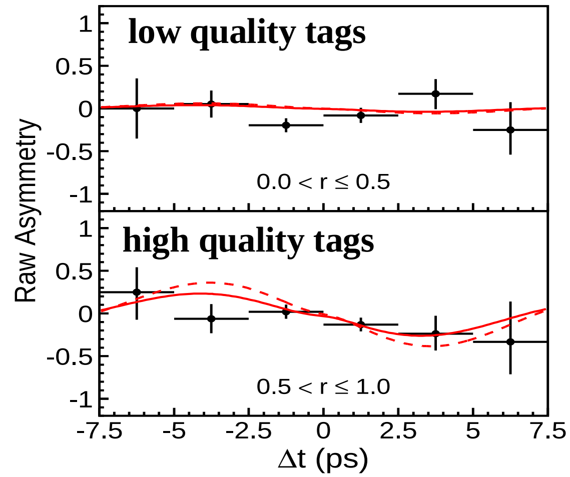
$N = 36 \pm 15$, 17% pure

$\sin(2\phi_1) = +0.06 \pm 0.33 \pm 0.09$, $A = +0.08 \pm 0.22 \pm 0.09$

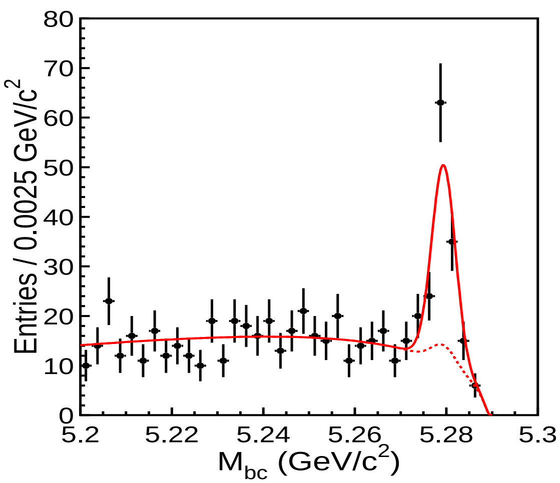
Measurement of $\sin(2\phi_1)$ *with* $b\to qqs$ **(hep-ex/0409049)**



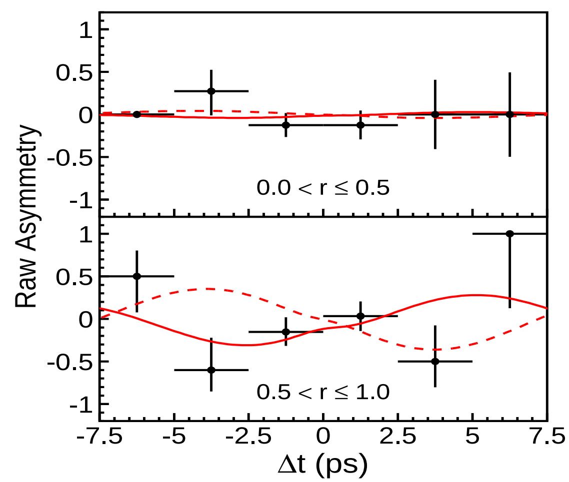
$B^0 \to K^+K^-K_S$
(CP = +1 mostly)
$N = 399 \pm 28$
56% pure



$\sin(2\phi_1) =$
$+0.49 \pm 0.18 \pm 0.04$
$A =$
$-0.08 \pm 0.12 \pm 0.07$

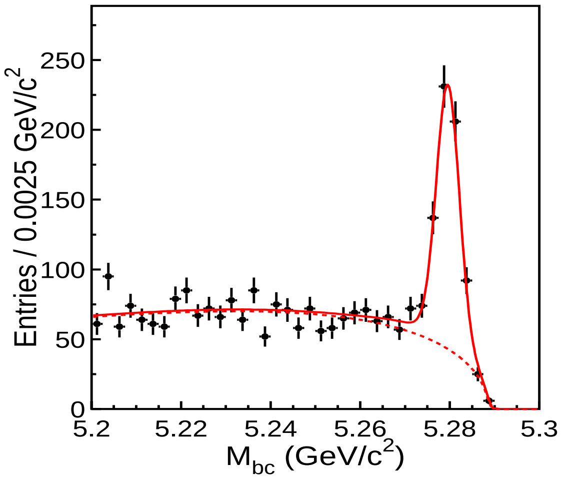


$B^0 \to f_0(980)K_S$
(CP = +1)
$N = 94 \pm 14$
53% pure

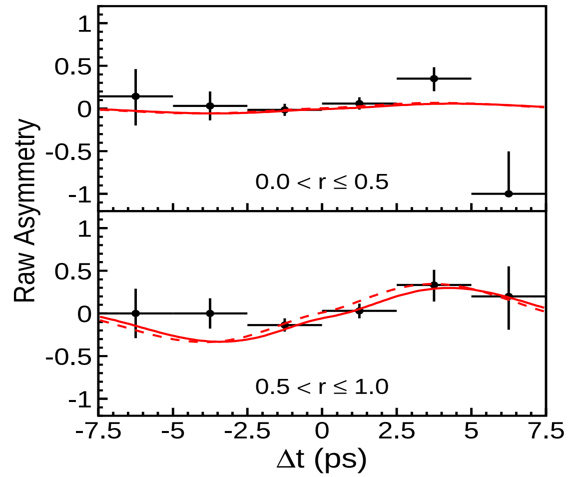


$\sin(2\phi_1) =$
$-0.47 \pm 0.41 \pm 0.08$
$A =$
$-0.39 \pm 0.27 \pm 0.08$

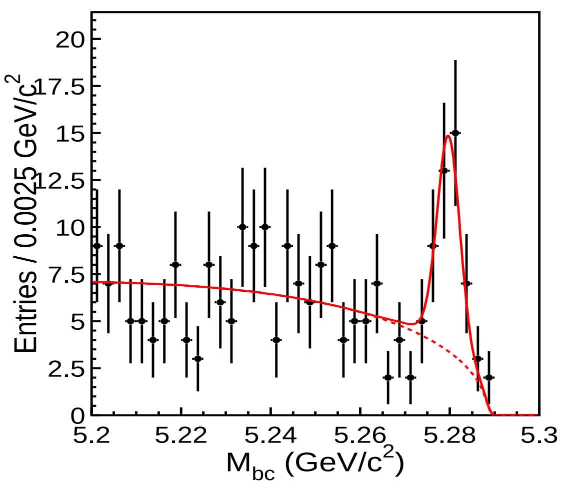
Measurement of sin(2ϕ_1) with b→qqs (hep-ex/0409049)



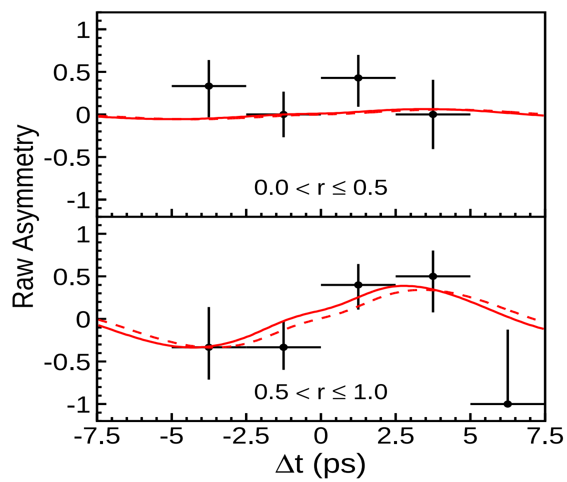
$B^0 \to \eta' K_s$
(CP = –1)
N = 512 ±27
61% pure



sin(2ϕ_1) =
+ 0.65 ±0.18±0.04
***A* =**
– 0.19 ±0.11±0.05

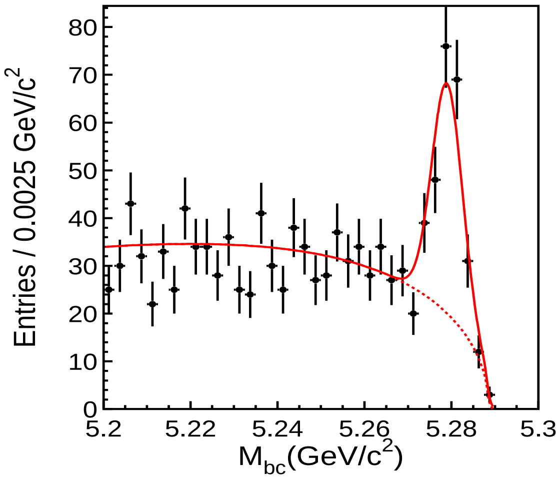


$B^0 \to \omega K_s$
(CP = –1)
N = 31 ±7
56% pure

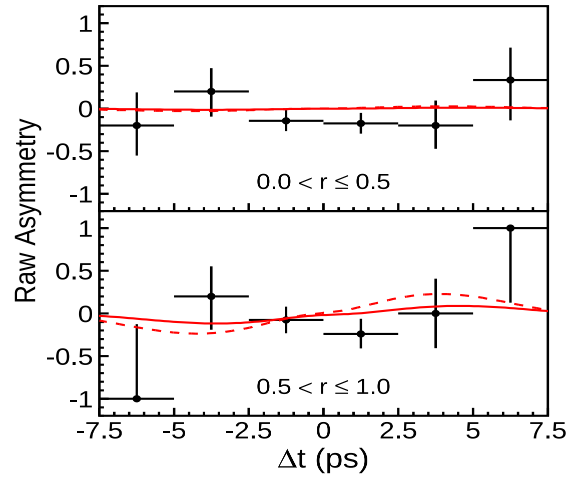


sin(2ϕ_1) =
+ 0.75 ±0.64 $^{+0.13}_{+0.16}$
***A* =**
+ 0.26 ±0.48±0.15

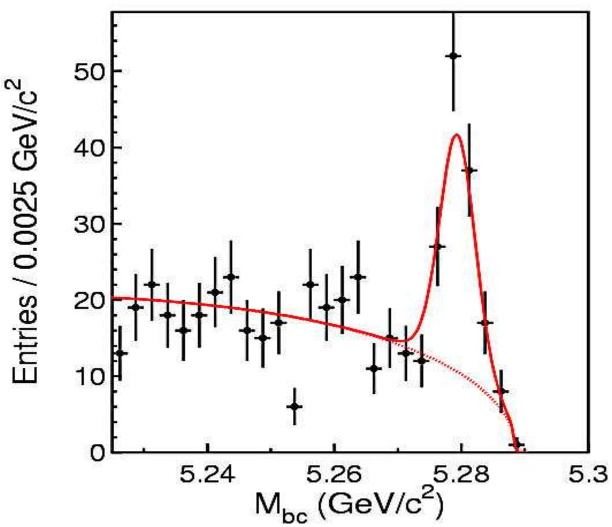
Measurement of sin(2ϕ_1) with $b \to qqs$ (hep-ex/0409049 hep-ex/0411056)



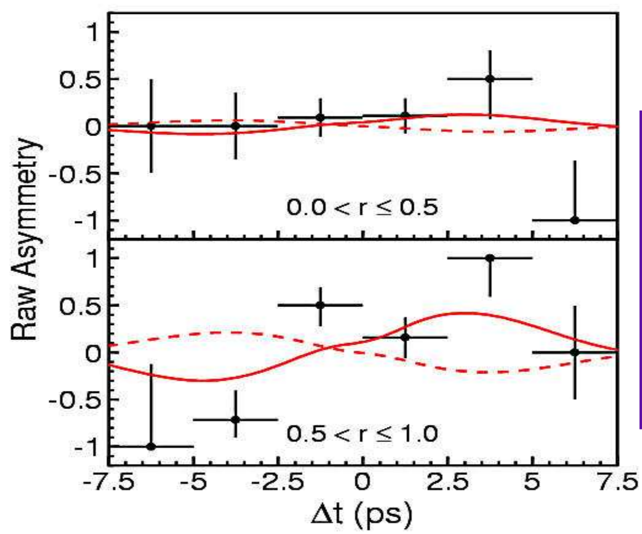
$B^0 \to \pi^0 K_S$
($CP = -1$)
$N = 251 \pm 24$
55/17% pure



$\sin(2\phi_1) =$
$+\,0.30 \pm 0.59 \pm 0.11$
$A =$
$-\,0.12 \pm 0.20 \pm 0.07$

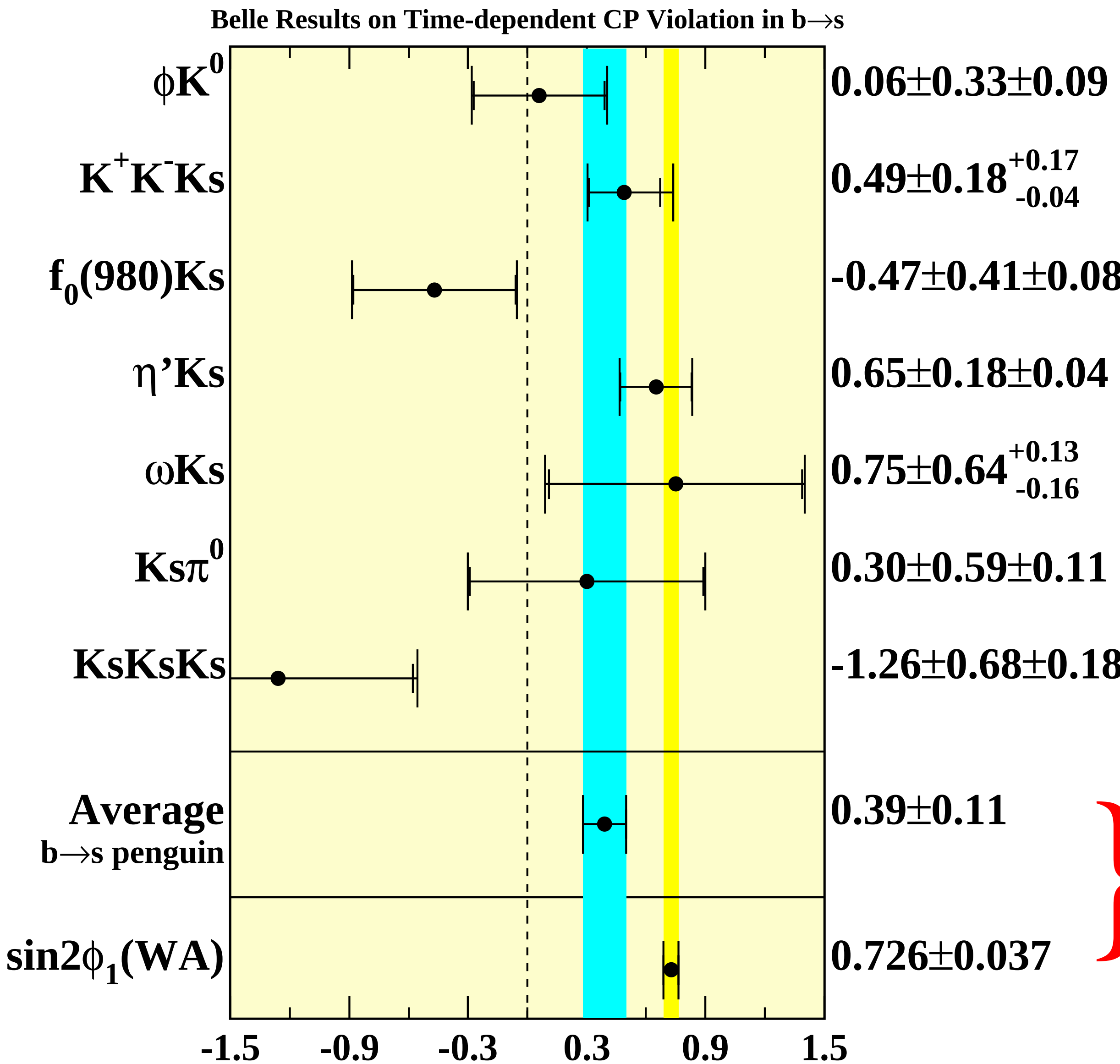


$B^0 \to K_S K_S K_S$
($CP = +1$)
$N = 88 \pm 13$
53% pure



$\sin(2\phi_1) =$
$-\,1.26 \pm 0.68 \pm 0.18$
$A =$
$+\,0.54 \pm 0.34 \pm 0.08$

Measurement of $\sin(2\phi_1)$ summary



2.9σ difference
⇒ more statistics needed

Measurement of sin(2ϕ_2) with $B^0 \to \pi^+\pi^-$

$$\lambda = \sqrt{\frac{M_{12}^*}{M_{12}}}\,\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} = +\left(\frac{V_{td}\,V_{tb}^*}{V_{td}^*\,V_{tb}}\right)\left(\frac{V_{ub}\,V_{ud}^*}{V_{ub}^*\,V_{ud}}\right)$$

$$= \frac{-V_{tb}^* V_{td}/(V_{ub}^* V_{ud})}{-V_{tb} V_{td}^*/(V_{ub} V_{ud}^*)}$$

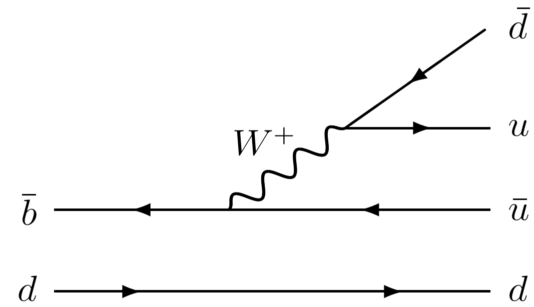
$$= \frac{|\mathcal{M}'|e^{i\phi_2}}{|\mathcal{M}'|e^{-i\phi_2}}$$

$$= e^{2i\phi_2}$$

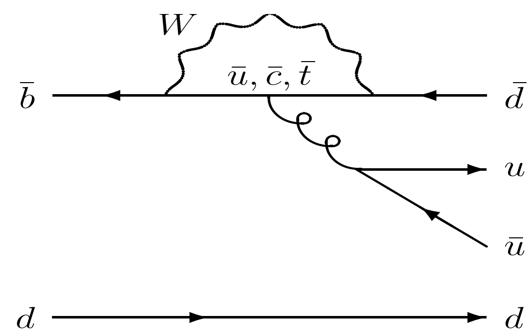
$$\Rightarrow \quad \mathcal{A}_{\pi\pi} = 0 \qquad \mathcal{S}_{\pi\pi} = \sin(2\phi_2)$$

...if no penguin. But there is a penguin contribution, which "breaks" these equalities

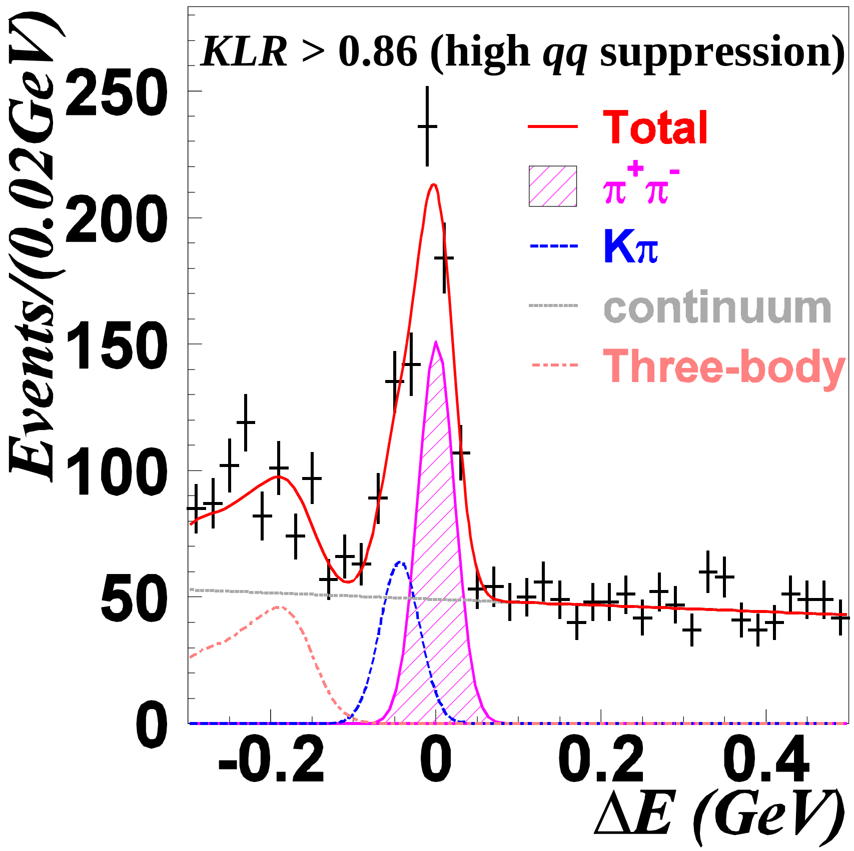
Tree:

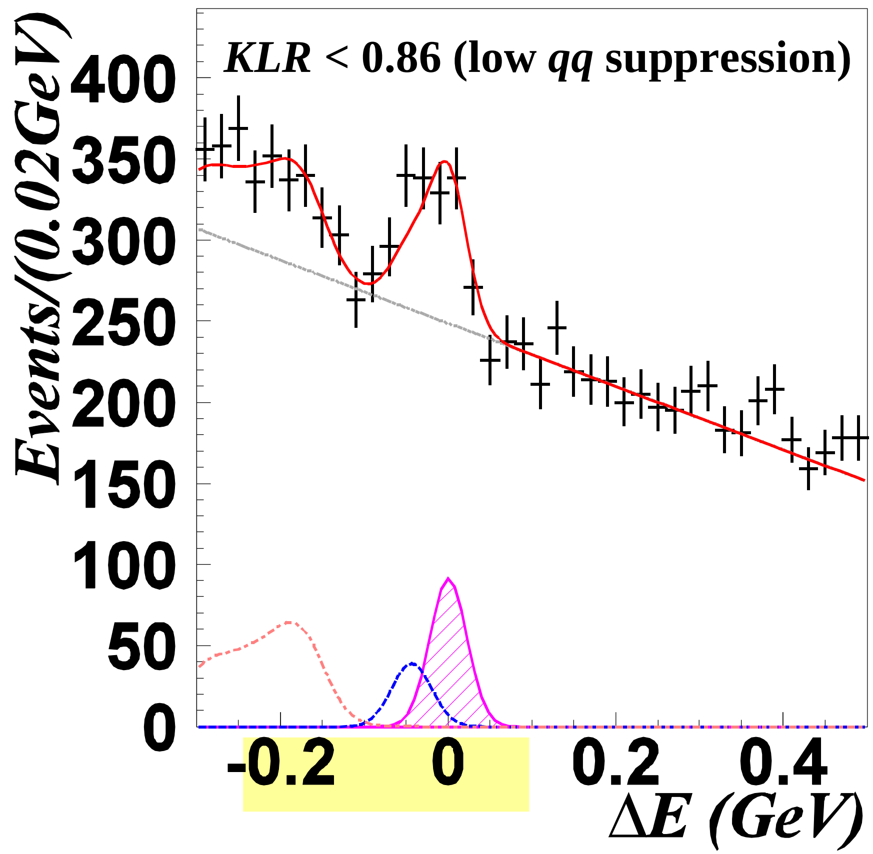


Penguin:



$B^0 \to \pi^+\pi^-$ sample (253 fb^{-1}) (hep-ex/0502035)

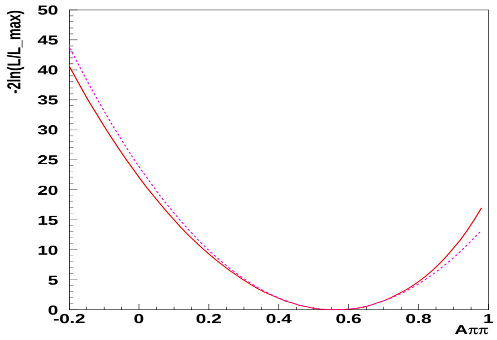




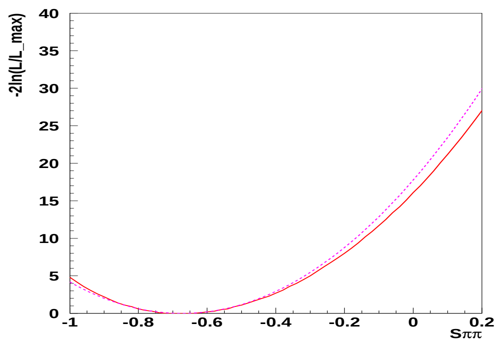
$N_{\pi\pi} = 415 \pm 13$

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

Results of Fit I (hep-ex/0502035)

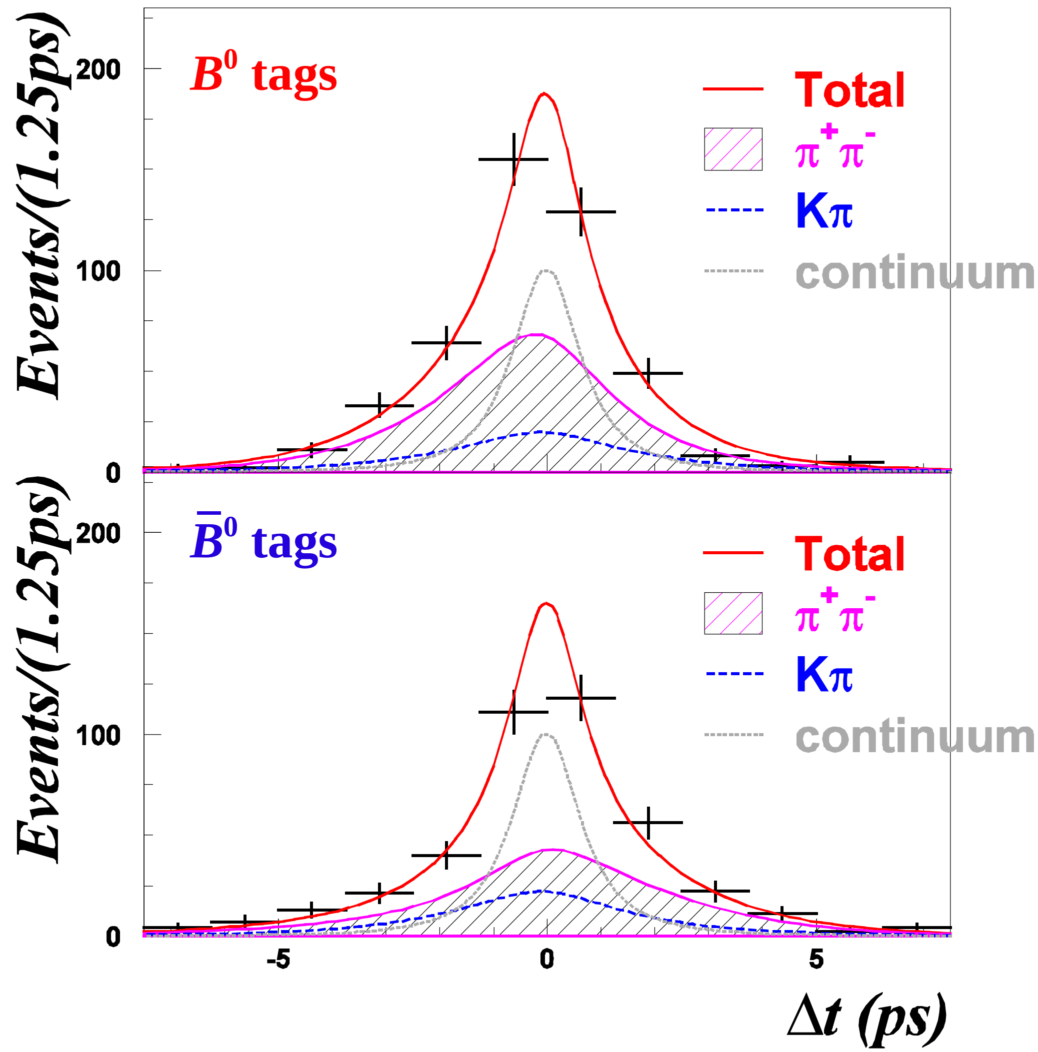


$A_{\pi\pi} = 0.56\ ^{+\,0.11}_{-\,0.12}$ (MINOS)



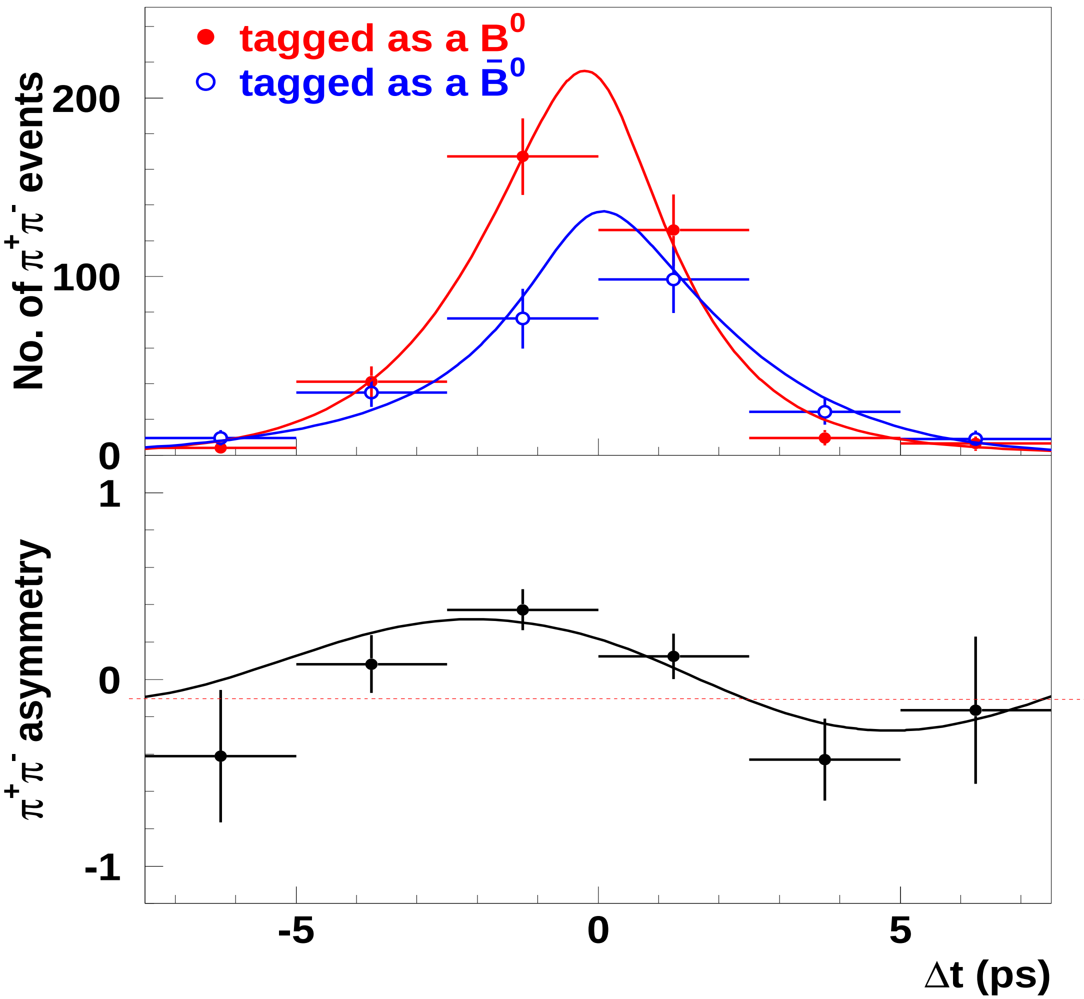
$S_{\pi\pi} = -0.67 \pm 0.16$ (MINOS)

KLR > 0.86, good tags



Results of Fit II (hep-ex/0502035)

m_{bc}-ΔE 2D fit for event yields in bins of Δt :



projection of Δt fit superimposed

($A_{\pi\pi}$ = 0.56

$S_{\pi\pi}$ = –0.67)

Systematic Uncertainties

Uncertainty	$A_{\pi\pi}$	$S_{\pi\pi}$
Wrong tag fraction	± 0.01	± 0.01
τ_B, Δm, $A_{K\pi}$	± 0.01	< 0.01
Resolution function	± 0.01	± 0.04
Background Δt shape	< 0.01	< 0.01
Background fractions	± 0.04	± 0.02
Fit bias	± 0.01	± 0.01
Vertexing	${}^{+0.03}_{-0.01}$	± 0.04
Tag side interference	${}^{+0.02}_{-0.04}$	± 0.01
Total	± 0.06	± 0.06

Background fractions: includes uncertainty in final state radiation

Tag side interference: O. Long *et al.*, PRD 68, 034010 (2003)

Constraints upon ϕ_2 (α) and |P/T|

Gronau and Rosner,
PRD 65, 093012, 2002:

$$A(B^0 \to \pi^+\pi^-) = -\left(|T|e^{i\delta_T}e^{i\phi_3} + |P|e^{i\delta_P}\right)$$
$$A(\overline{B}^0 \to \pi^+\pi^-) = -\left(|T|e^{i\delta_T}e^{-i\phi_3} + |P|e^{i\delta_P}\right)$$

$$\Rightarrow \quad \lambda_{\pi\pi} \equiv \frac{q}{p}\frac{\overline{A}_{\pi\pi}}{A_{\pi\pi}} = e^{i\phi_2}\frac{1+|P/T|\,e^{i(\delta+\phi_3)}}{1+|P/T|\,e^{i(\delta-\phi_3)}}$$

$$(\delta \equiv \delta_P - \delta_T)$$

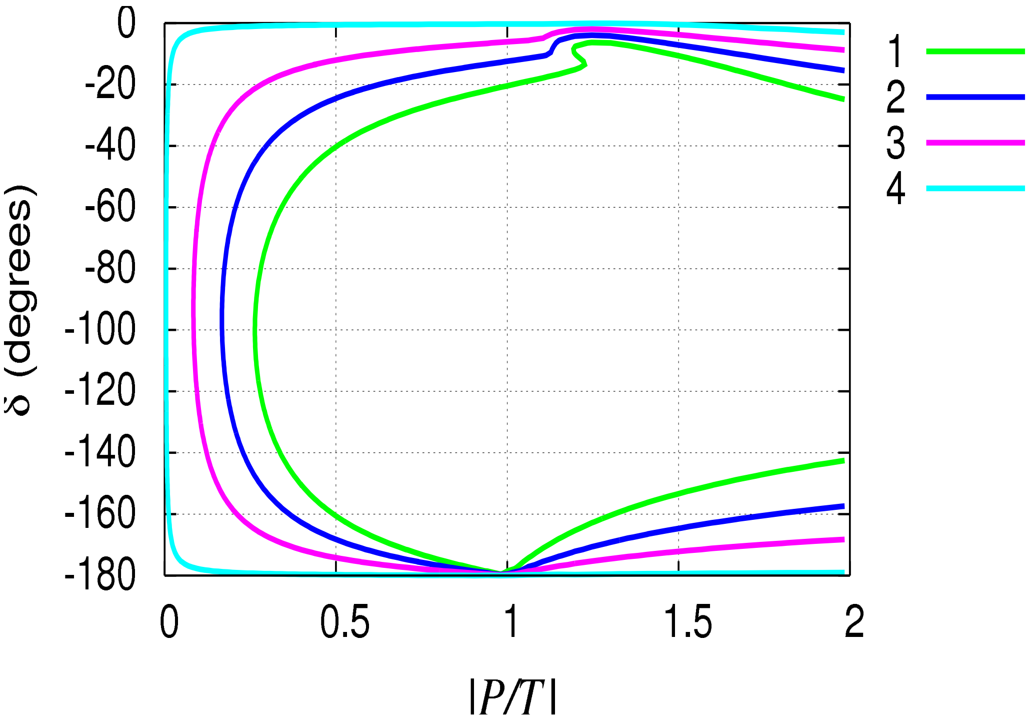
Take ϕ_1 = 0.725 ±0.037
⇒ 2 constraints &
3 unknowns
(ϕ_2, δ, |P/T|)

$$A_{\pi\pi} \equiv \frac{|\lambda|^2-1}{|\lambda|^2+1} = \frac{-2|P/T|\sin(\phi_1+\phi_2)\sin\delta}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

$$S_{\pi\pi} \equiv \frac{2Im\lambda}{|\lambda|^2+1}$$

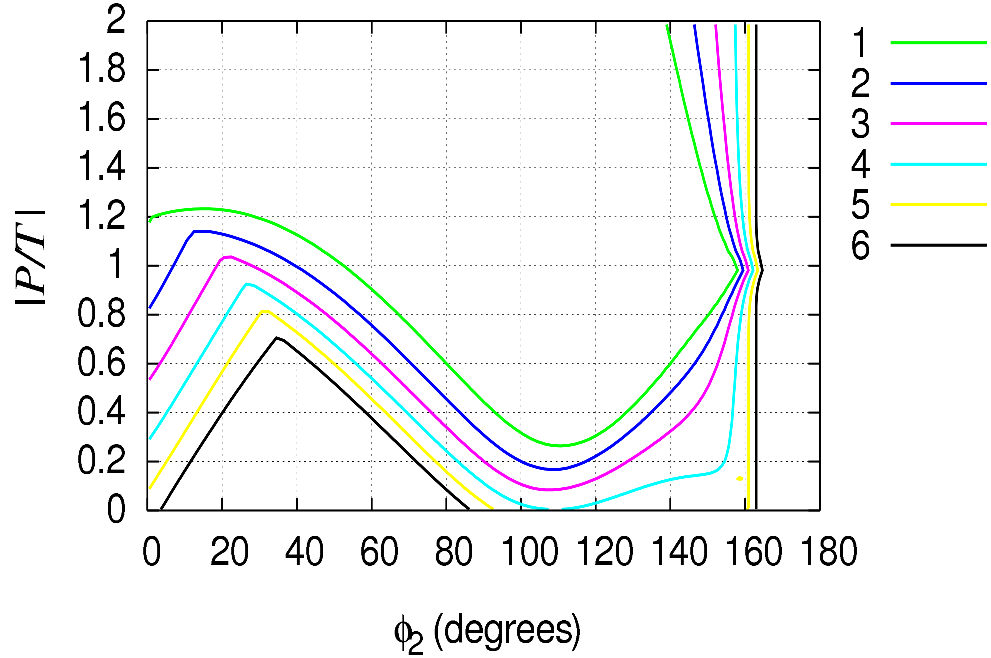
$$= \frac{2|P/T|\sin(\phi_1-\phi_2)\cos\delta+\sin 2\phi_2-|P/T|^2\sin 2\phi_1}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

Constraints upon ϕ_2 (α) and $|P/T|$ cont'd



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

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



Isospin analysis for ϕ_2

SU(2) isospin analysis:

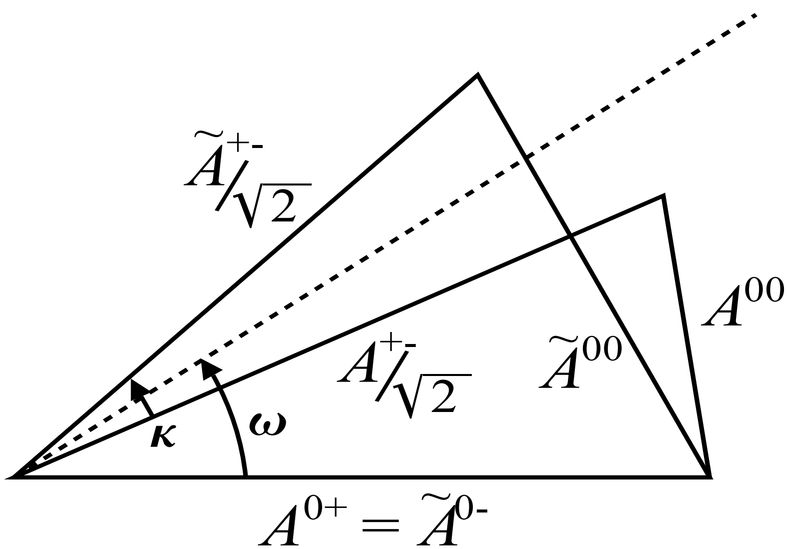
Gronau and London,
PRL 65, 3381 (1990)

$$\frac{A(B^0\to\pi^+\pi^-)}{\sqrt{2}} + A(B^0\to\pi^0\pi^0) = A(B^+\to\pi^+\pi^0)$$

$$\frac{A(\overline{B}^0\to\pi^+\pi^-)}{\sqrt{2}} + A(\overline{B}^0\to\pi^0\pi^0) = A(B^-\to\pi^-\pi^0)$$

6 param. + 6 observables $\Rightarrow$ all determined

Recent measurements (253 fb^{-1}) of $\bar{B}^0(B^0)\to\pi^0\pi^0$ now make this possible



$$|A^{+-}_{\rm th}| = \sqrt{a^{+-}(1-\mathcal{A}_{\pi\pi})}$$
$$|\overline{A}^{+-}_{\rm th}| = \sqrt{a^{+-}(1+\mathcal{A}_{\pi\pi})}$$
$$|A^{0-}_{\rm th}| = |A^{0+}_{\rm th}| = \sqrt{a^{0+}}$$
$$|A^{00}_{\rm th}|^2 = \frac{|A^{+-}_{\rm th}|^2}{2} + |A^{0+}_{\rm th}|^2 - \sqrt{2}\,|A^{+-}_{\rm th}|\,|A^{+0}_{\rm th}|\cos(\omega-\kappa/2)$$
$$|\overline{A}^{00}_{\rm th}|^2 = \frac{|\overline{A}^{+-}_{\rm th}|^2}{2} + |A^{0+}_{\rm th}|^2 - \sqrt{2}\,|\overline{A}^{+-}_{\rm th}|\,|A^{+0}_{\rm th}|\cos(\omega+\kappa/2)$$
$$B^{\pi^+\pi^-}_{\rm th} = \left(|A^{+-}_{\rm th}|^2 + |\overline{A}^{+-}_{\rm th}|^2\right)/2 = a^{+-}$$
$$B^{\pi^0\pi^0}_{\rm th} = \left(|A^{00}_{\rm th}|^2 + |\overline{A}^{00}_{\rm th}|^2\right)/2$$
$$B^{\pi^0\pi^+}_{\rm th} = |A^{0+}_{\rm th}|^2\,(\tau_{B^\pm}/\tau_{B^0}) = a^{+0}\cdot(\tau_{B^\pm}/\tau_{B^0})$$
$$\mathcal{A}^{\pi^0\pi^0}_{\rm th} = \frac{|\overline{A}^{00}_{\rm th}|^2 - |A^{00}_{\rm th}|^2}{|\overline{A}^{00}_{\rm th}|^2 + |A^{00}_{\rm th}|^2}$$
$$\mathcal{A}^{\pi^+\pi^-}_{\rm th} = \mathcal{A}_{\pi\pi}$$
$$\mathcal{S}^{\pi^+\pi^-}_{\rm th} = \sqrt{1-\mathcal{A}'^2_{\pi\pi}}\;\sin(2\phi_2+\kappa)$$

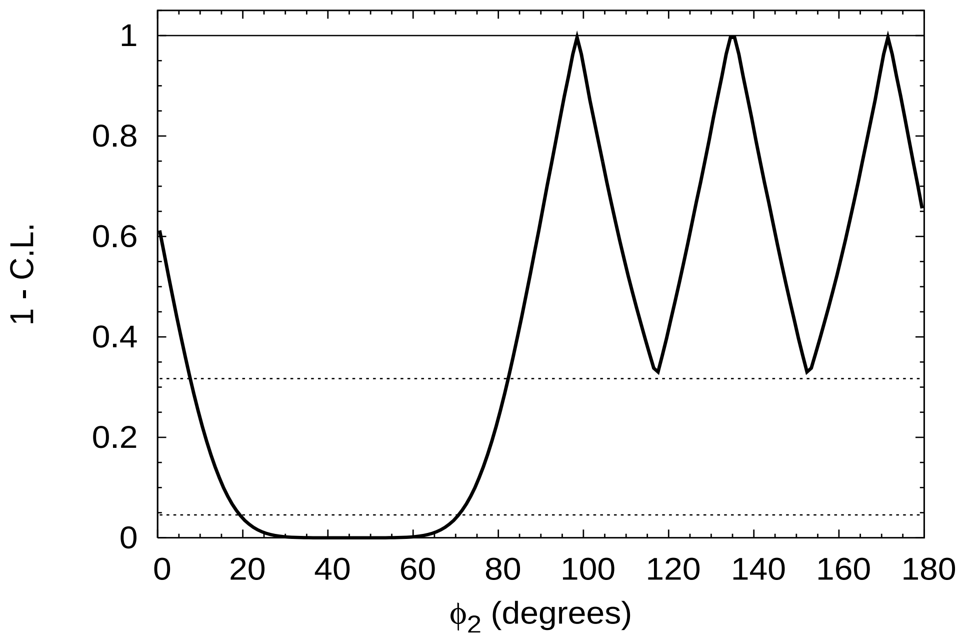
Isospin analysis for ϕ_2 cont'd

(hep-ex/0502035)

Use HFAG values for $B(\pi^+\pi^-)$, $B(\pi^+\pi^0)$, $B(\pi^0\pi^0)$, $\mathcal{A}(\pi^0\pi^0)$

Calculate χ^2 :

$$\chi^2(\vec{y}) = \sum \frac{(x_{\rm exp} - x_{\rm th})^2}{\sigma^2_{\rm exp}} + \chi^2_{FC}\left(\mathcal{A}_{\rm th}^{\pi^+\pi^-}, \mathcal{S}_{\rm th}^{\pi^+\pi^-}\right)$$



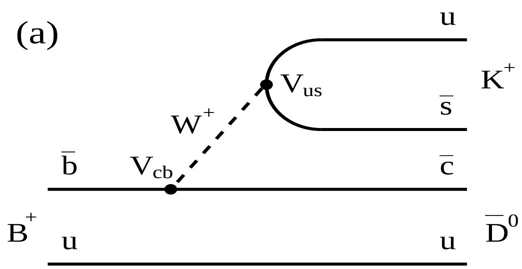
$0^{\rm o} < \phi_2 < 19^{\rm o}$ and $71^{\rm o} < \phi_2 < 180^{\rm o}$ (95% CL)

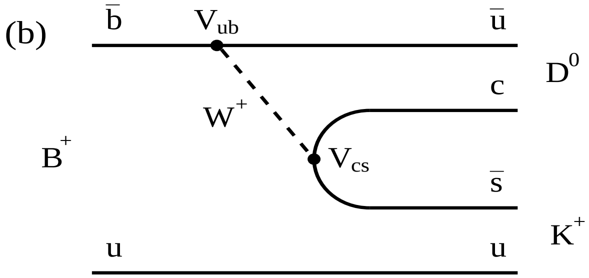
Note: preliminary

Measurement of ϕ_3

A. Bondar *et al.*, 2002 (unpublished);
Giri *et al.*, PRD 68, 054018, 2003

$B^+ \to \bar{D}^{0(*)} K^+$ $\quad$ $B^+ \to D^{0(*)} K^+$





if $\bar{D}^0/D^0 \to K_s \pi^+\pi^-$, amplitudes interfere

$$m_+ = m(K_s^0, \pi^+)$$
$$m_- = m(K_s^0, \pi^-)$$
$$r = \left|\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \bar{D}^0 K^+)}\right| \sim 0.1 - 0.2$$

$$M_+ = A(m_+^2, m_-^2) + r e^{i(\delta+\phi_3)} A(m_-^2, m_+^2)$$

$$M_- = A(m_-^2, m_+^2) + r e^{i(\delta-\phi_3)} A(m_+^2, m_-^2)$$

$$|M_\pm|^2 = (r^2)_- \left|A(m_+^2, m_-^2)\right|^2 + (r^2)_+ \left|A(m_-^2, m_+^2)\right|^2 + 2\left|A(m_+^2, m_-^2)\right|\left|A(m_-^2, m_+^2)\right| r \cos(\delta + \theta_{(m_+^2, m_-^2)} \pm \phi_3)$$

amplitude A determined from $D^0 \to K_s \pi^+\pi^-$ Dalitz plot (from continuum)

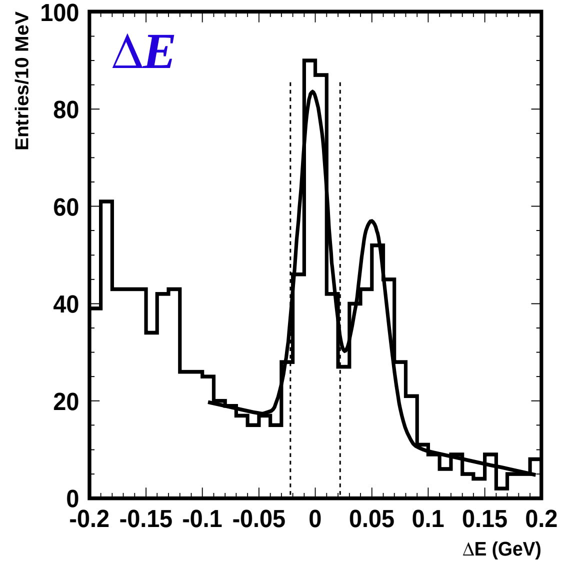
Measurement of ϕ_3 (hep-ex/0411049)

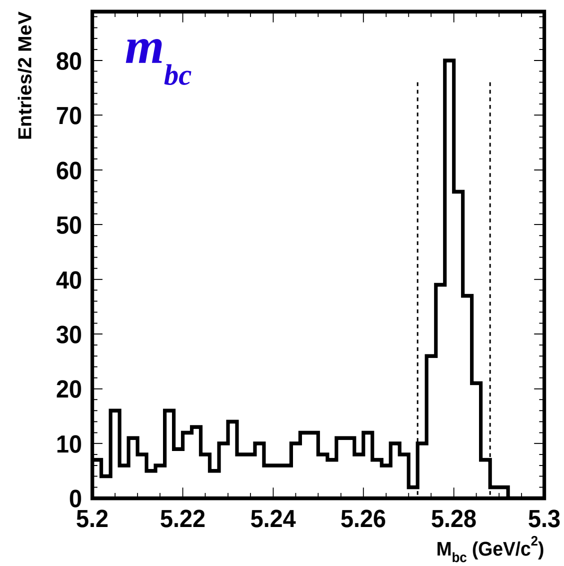
253 fb $^{-1}$

$B^{\pm} \to D^0 K^{\pm}$:

$N = 209 \pm 16$

75% pure

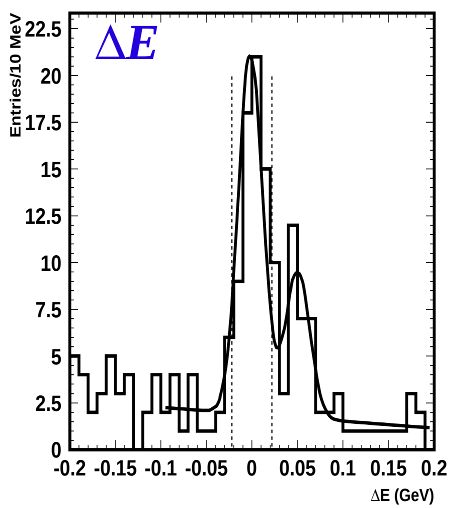


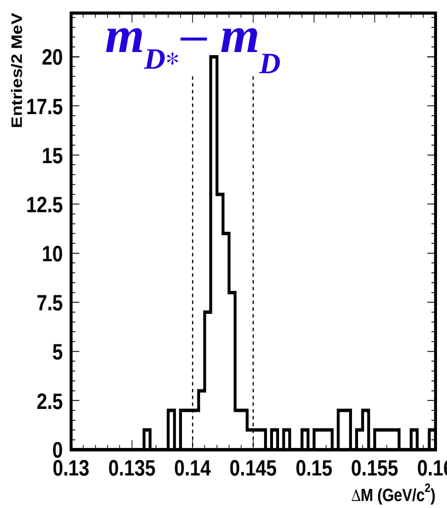


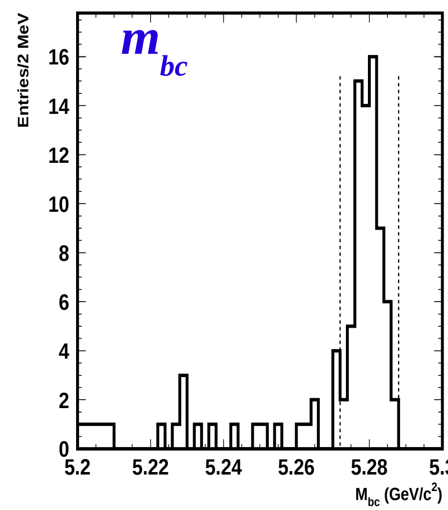
$B^{\pm} \to D^{0*} K^{\pm}$:

$N = 58 \pm 8$

87% pure

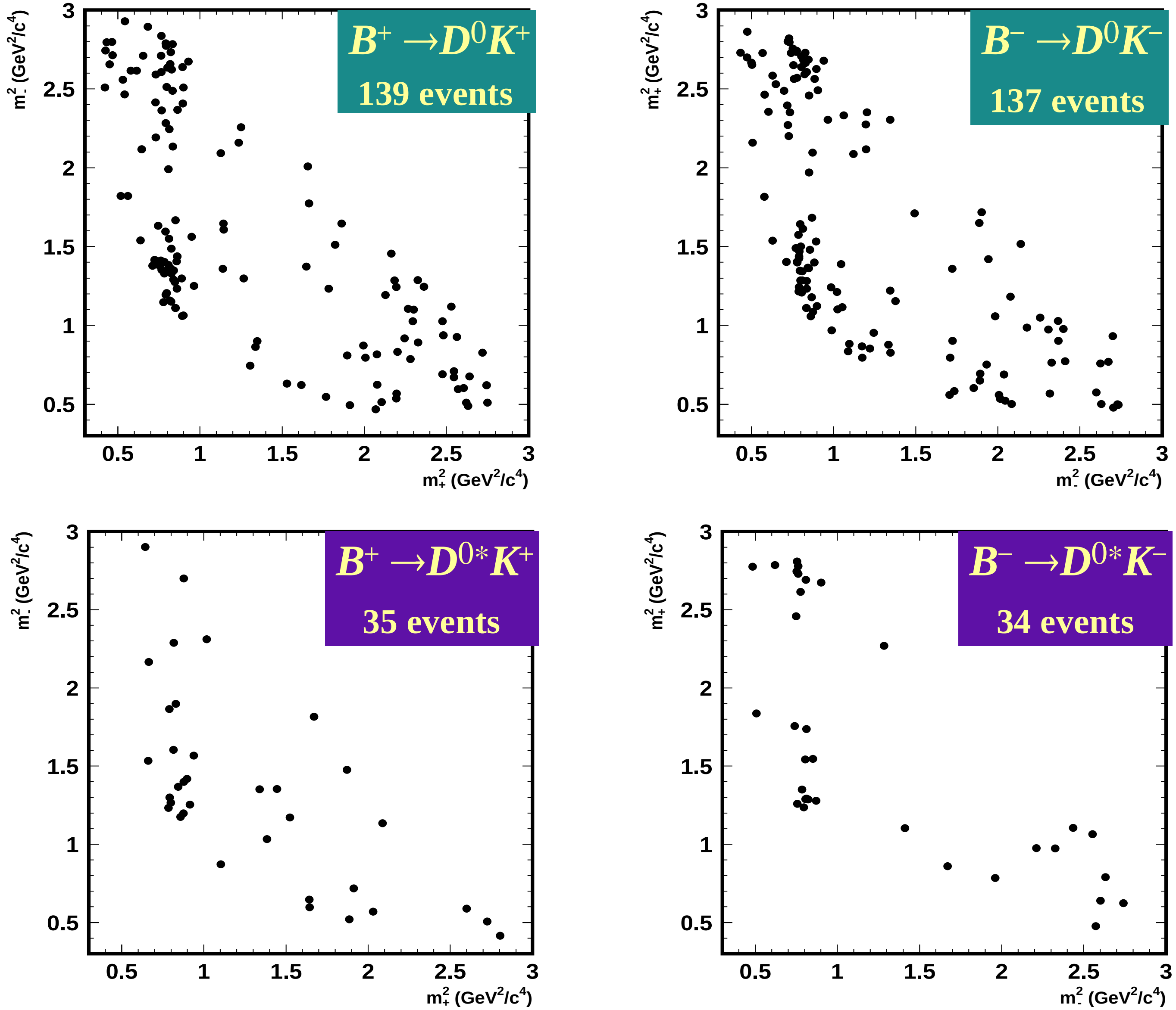






Measurement of ϕ_3 (hep-ex/0411049)

253 fb $^{-1}$



Measurement of ϕ_3 (hep-ex/0411049)

Do unbinned ML fit for ϕ_3, δ, r

Use toy MC with Feldman-Cousins ordering to calculate frequentist confidence regions for parameters ϕ_2, δ, r

Projecting 2σ regions for
$(B^\pm \rightarrow D^0 K^\pm) + (B^\pm \rightarrow D^{0*} K^\pm)$:

$\phi_3 = (68\,^{+14}_{+15} \pm 13 \pm 11)^o$

$22^o < \phi_3 < 113^o$ (95% CL)

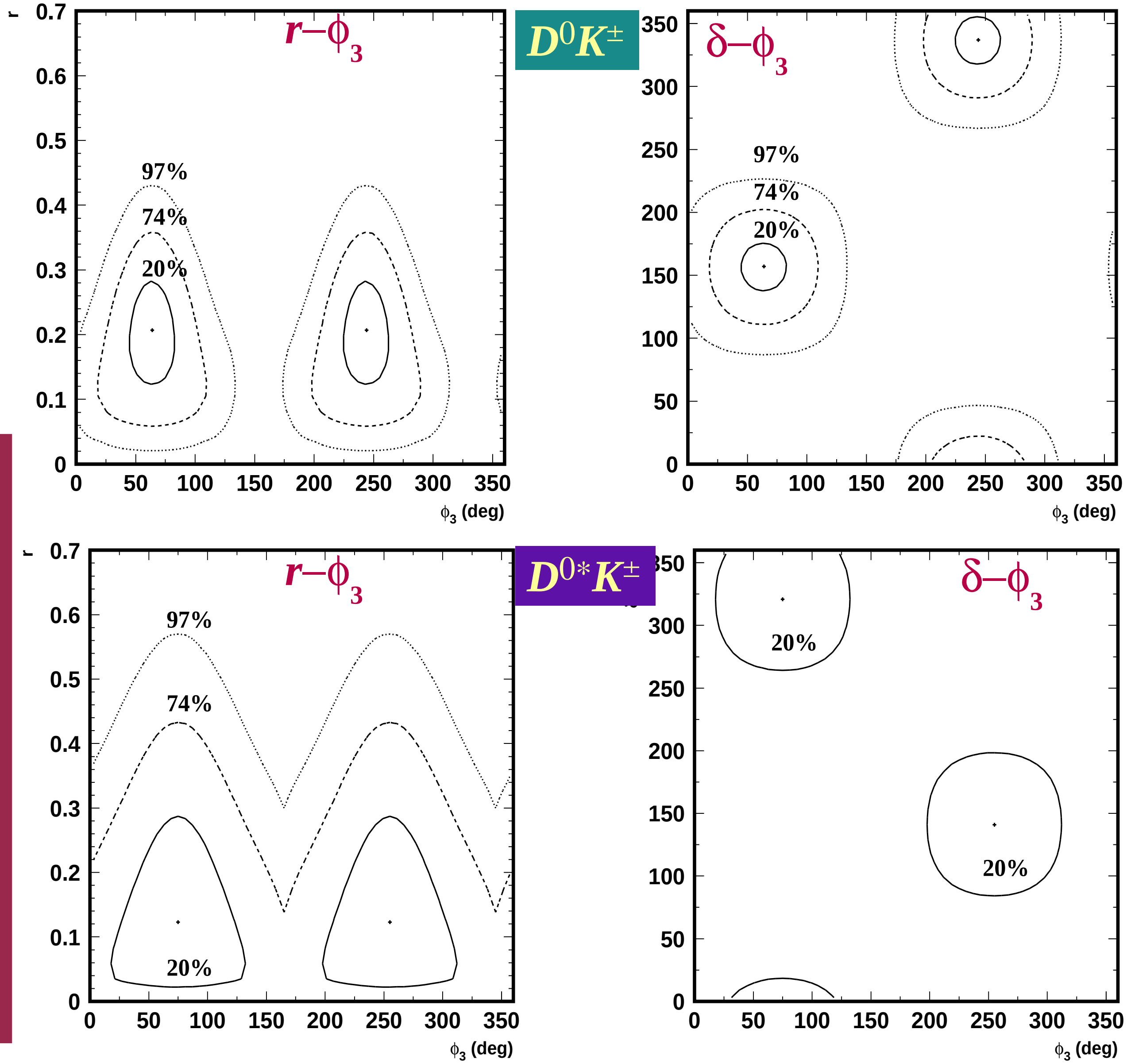
$\delta_D = (157 \pm 19 \pm 11 \pm 21)^o$

$\delta_{D*} = (321 \pm 57 \pm 11 \pm 21)^o$

$r_D = 0.21 \pm 0.08 \pm 0.03 \pm 0.04$

$r_{D*} = 0.12\,^{+0.16}_{+0.11} \pm 0.02 \pm 0.04$

CL of *CPV* = 98%



Summary

140 fb^{-1} :

- $\sin(2\phi_1)$: $0.728 \pm 0.056 \pm 0.023$ $\Rightarrow$ $\phi_1 = (23.4^{+2.7}_{-2.4})^o$

  $b \to qqs$ penguin: 0.39 ± 0.11 (2.3σ difference)

253 fb^{-1} :

- $\sin(2\phi_2)$: we have observed compelling *CP* violation in $B \to \pi^+\pi^-$ decays: $A_{\pi\pi} = +0.56 \pm 0.12$ (stat) ± 0.06 (syst)

  $S_{\pi\pi} = -0.67 \pm 0.16$ (stat) ± 0.06 (syst)

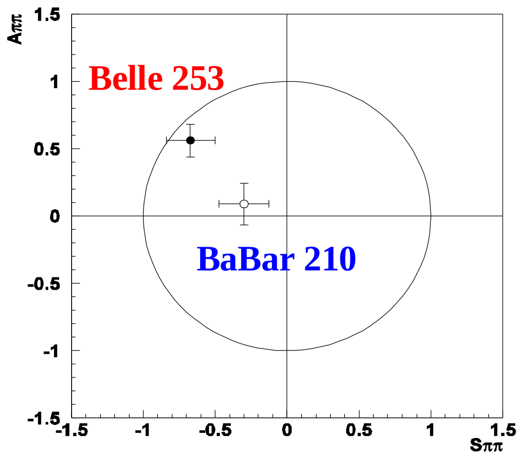
  $A_{\pi\pi}$ indicates direct *CPV* at 4σ significance

  $\Rightarrow$ $|P/T| > 0.17$ (95% CL) $\delta < -4^o$ (95% CL)

  An isospin analysis of $B \to \pi\pi$ decays gives

  $0^o < \phi_2 < 19^o$ and $71^o < \phi_2 < 180^o$ (95% CL)

  $|\phi_2(\text{eff}) - \phi_2| < 38^o$ (95% CL)



253 fb^{-1} :

- ϕ_3 : $(68^{+14}_{-15} \pm 13 \pm 11)^o$

  $22^o < \phi_3 < 113^o$ (95% CL)

  CL of *CP* violation = 98%

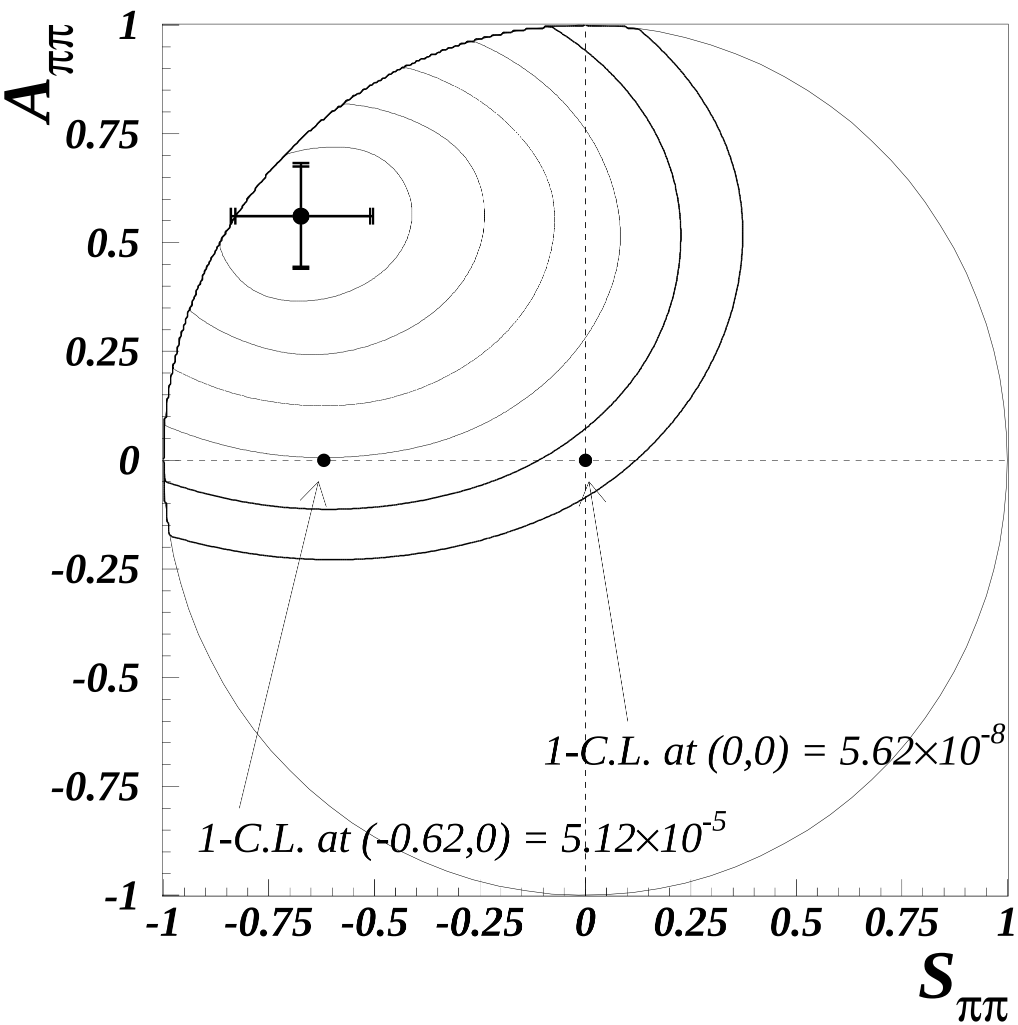
$\Rightarrow$ $\phi_1 + \phi_2 + \phi_3 - 180^o = (12.3 \pm 29.7)^o$

Backup slides

Statistical Significance

Use Toy MC, constructing confidence belts with Feldman-Cousins ordering

(Note: systematic errors are folded in)

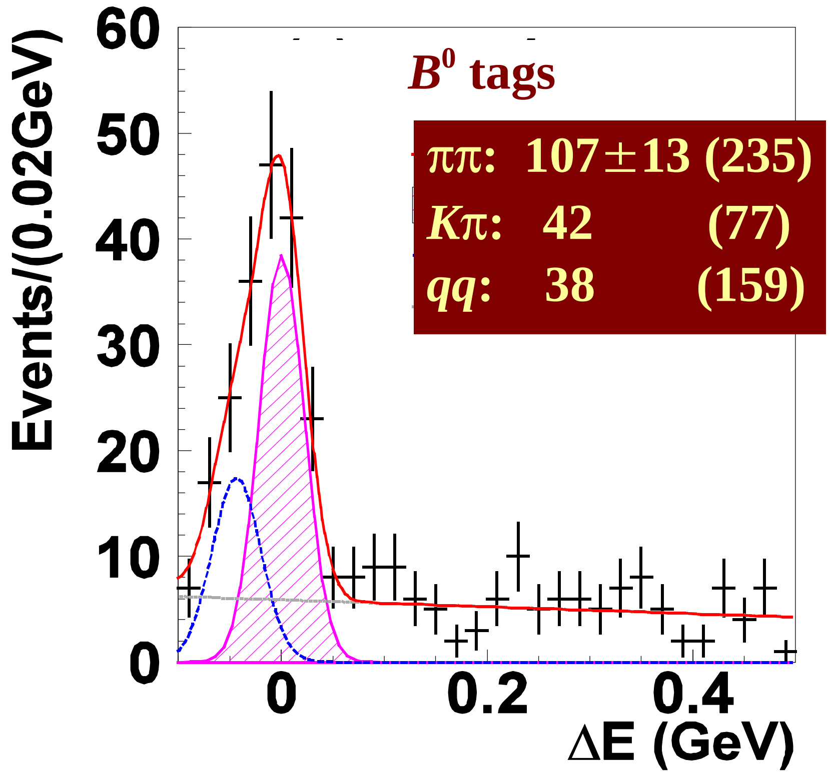


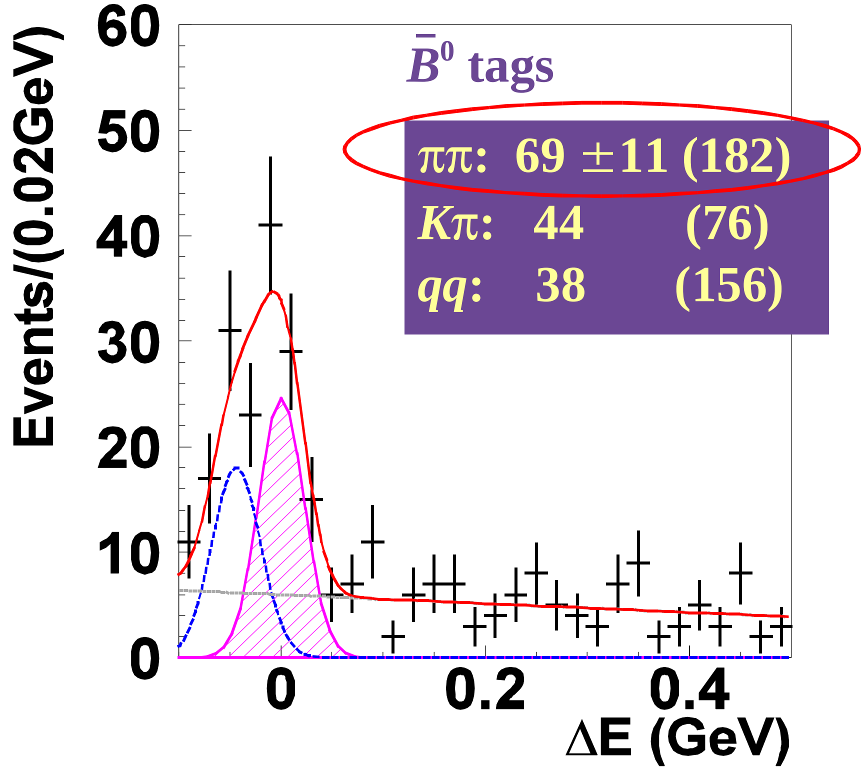
CL for (0, 0) corresponds to 5.4σ fluctuation ⇒ clear *CP* violation

CL for $A_{\pi\pi}$ = 0 corresponds to 4.0σ fluctuation (any $S_{\pi\pi}$) ⇒ direct *CP* violation

Check with time-integrated yields

KLR > 0.86 and good tags (all tags):





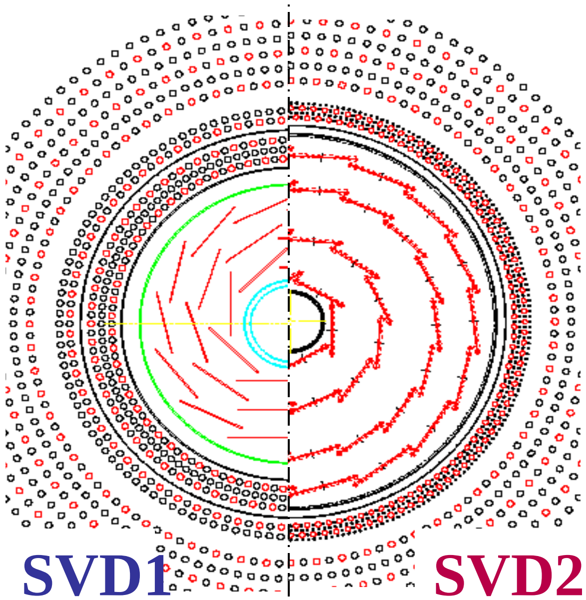
⇒ direct *CP* violation is clear

$$f_{\pi\pi}^{(q)} \propto 1 - q\Delta w_\ell + \frac{q(1-2w_\ell)}{1+x^2} A_{\pi\pi} \quad \Rightarrow A_{\pi\pi} = \mathbf{0.52 \pm 0.14}$$

consistent with Δ*t* fit

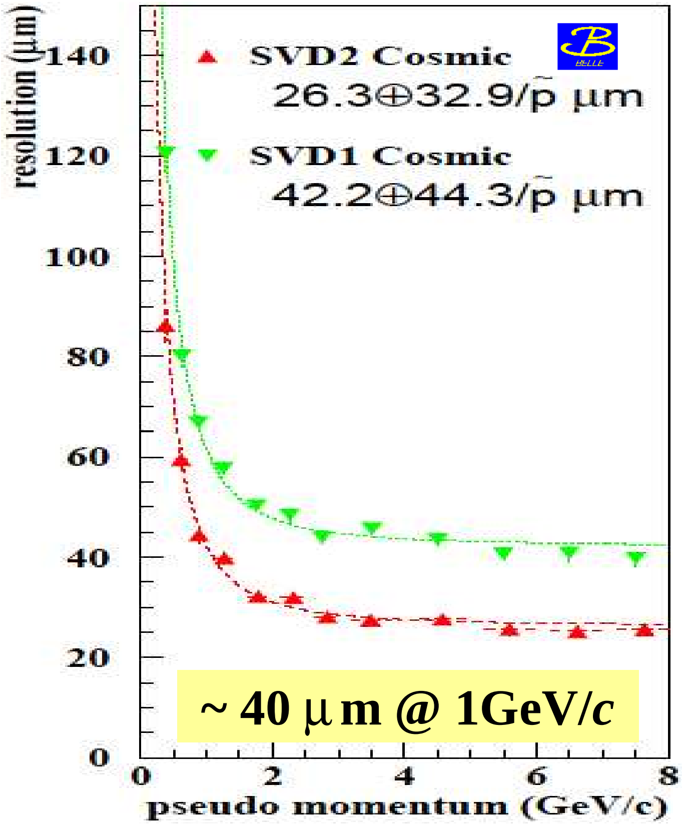
New data set since last result (140 + 113 fb^{-1})

SVD upgrade: better I.P. resolution
(also higher efficiency for K_s vertexing)



1 MRad → > 20 MRad
3 layers → 4 layers
23º< θ < 139º → 17º<θ<150º
R_{bp} = 2 cm → 1.5 cm

impact parameter resolution (*z*):



152 M *BB* pairs with SVD1
123 M *BB* pairs with SVD2

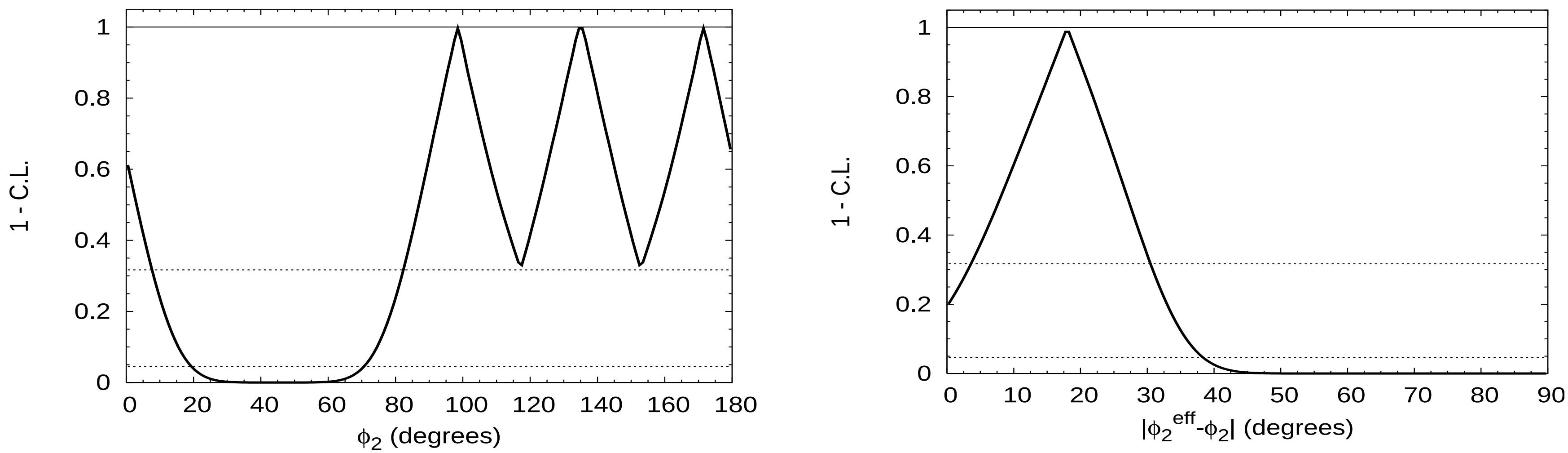
Isospin analysis for ϕ_2 cont'd

(hep-ex/0502035)

Use HFAG values for $B(\pi^+\pi^-)$, $B(\pi^+\pi^0)$, $B(\pi^0\pi^0)$, $\mathcal{A}(\pi^0\pi^0)$

Calculate χ^2 :

$$\chi^2(\vec{y}) = \sum \frac{(x_{\rm exp} - x_{\rm th})^2}{\sigma^2_{\rm exp}} + \chi^2_{FC}\,(\mathcal{A}^{\pi^+\pi^-}_{\rm th}, \mathcal{S}^{\pi^+\pi^-}_{\rm th})$$



$0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$ (95% CL)

$|\phi_2(\text{eff}) - \phi_2| < 38^\circ$ (95% CL)

Note: preliminary

Maximum likelihood fit to Δt

$$\mathcal{L}_i = \int \Big[f_{\pi\pi} P_{\pi\pi}(\Delta t') + f_{K\pi} P_{K\pi}(\Delta t') \Big] \cdot R_{hh}(\Delta t_i - \Delta t') + f_{q\bar{q}} P_{q\bar{q}}(\Delta t') \cdot R_{q\bar{q}}(\Delta t_i - \Delta t')\, dt'$$

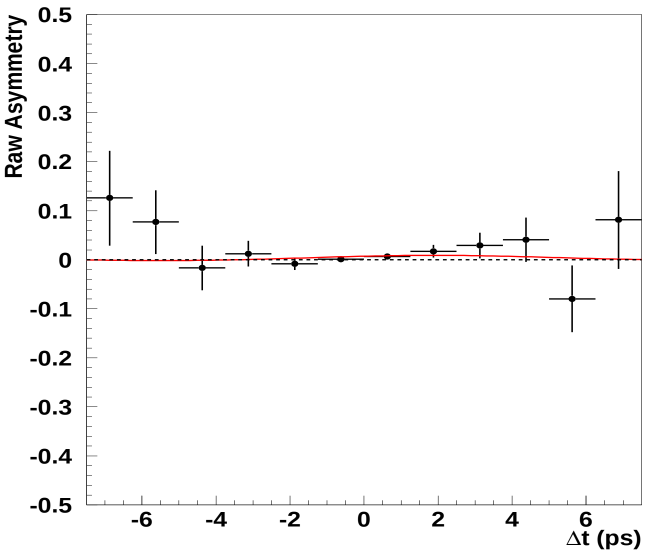
$$P^{(\ell)}_{B^0\to\pi\pi} = \frac{e^{-|\Delta t|/\tau_B}}{\mathcal{N}} \Big\{ 1 + q(1-2\omega_\ell)\big[\mathcal{A}_{\pi\pi}\cos(\Delta m\,\Delta t) + \mathcal{S}_{\pi\pi}\sin(\Delta m\,\Delta t)\big] \Big\}$$

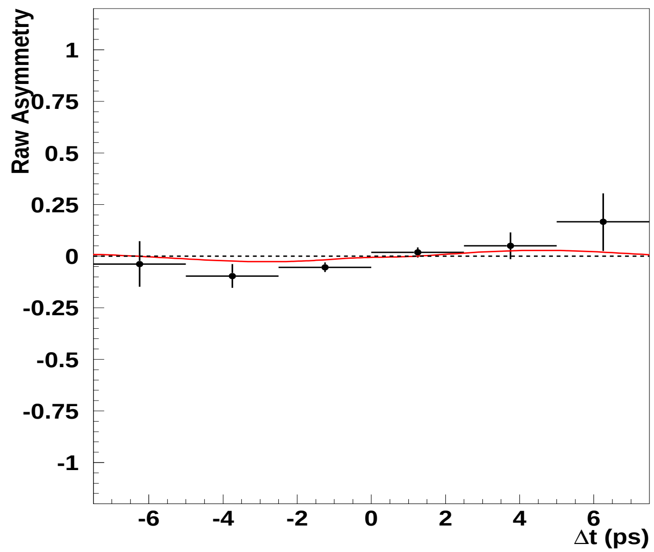
$$P_{K\pi} = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \Big\{ 1 + q(1-2\omega_\ell)\mathcal{A}^{\rm eff}_{K\pi}\cos(\Delta m\,\Delta t) \Big\} \qquad (\mathcal{A}_{K\pi} = -0.109 \pm 0.019)$$

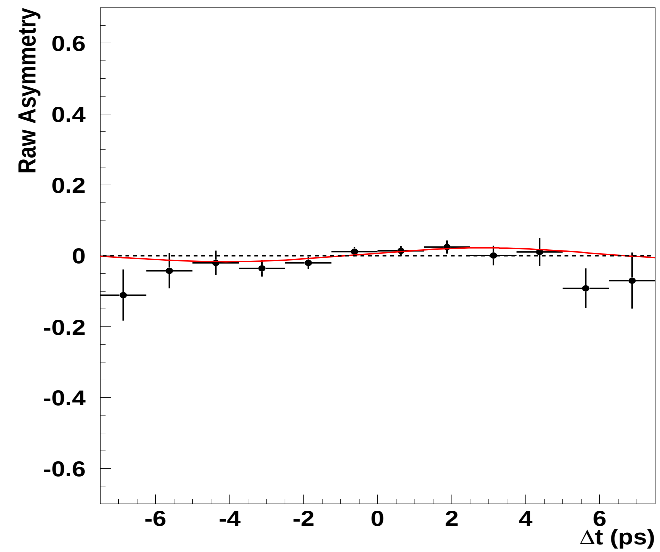
$$P_{q\bar{q}} = f\,\frac{e^{-|\Delta t|/\tau_{q\bar{q}}}}{2\tau_{q\bar{q}}} + (1-f)\,\delta(\Delta t)\,,$$

$$f_{\pi\pi} = \frac{F_{\pi\pi}(\Delta E, M_{bc})\cdot f_\ell(\pi\pi)}{\big[F_{\pi\pi}(\Delta E, M_{bc}) + F_{K\pi}(\Delta E, M_{bc})\big]\cdot f_\ell(\pi\pi) + F_{q\bar{q}}(\Delta E, M_{bc})\cdot f_\ell(q\bar{q})}$$

Cross checks I: other CP asymmetries







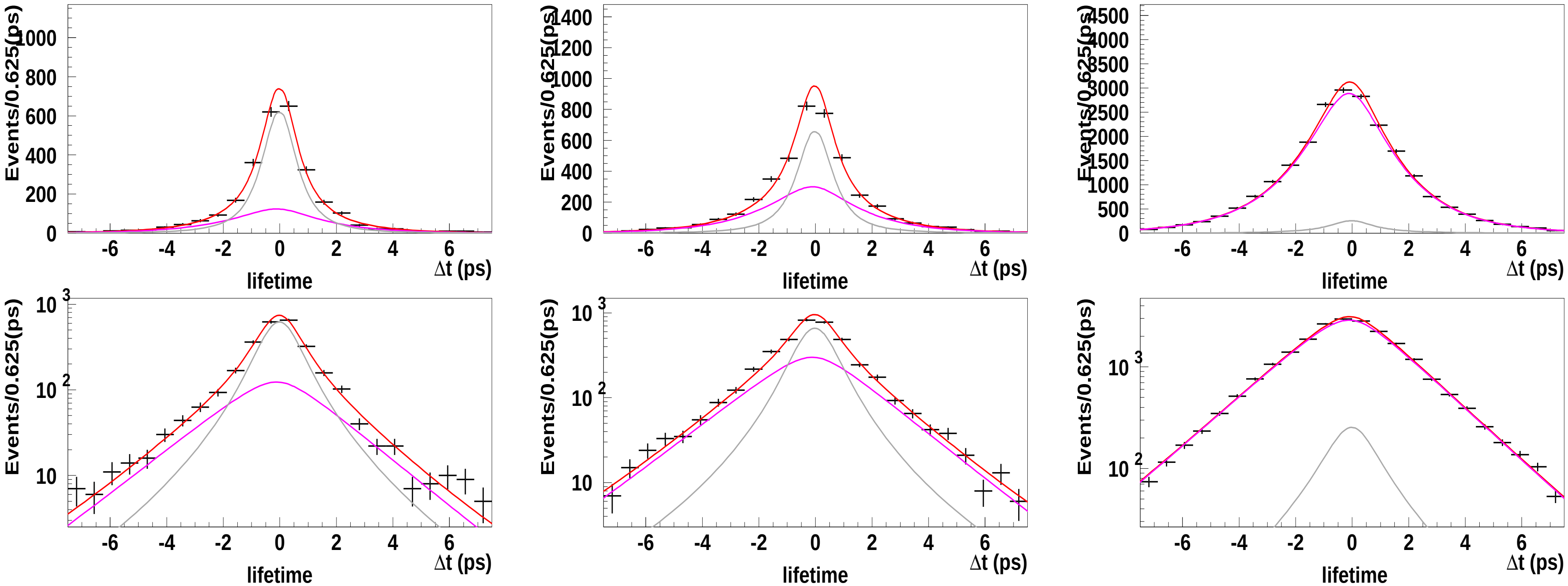
***qq* sideband:**
42467 B^0 tags
42090 B^0 tags
A = 0.017 ±0.011
S = 0.021 ±0.030

$B \to K^{\pm}\pi^{\mp}$:
2106 B^0 tags
2187 B^0 tags
A = –0.064 ±0.057
S = 0.091 ±0.079

$B \to D^{(*)\pm}\pi^{\mp}$:
11519 B^0 tags
11489 B^0 tags
A = 0.013 ±0.016
S = 0.057 ±0.024

⇒ Possible asymmetries are included in the systematic error

Cross checks II: τ_B



2820 $B \to \pi^+\pi^-$ cand:
τ_B = 1.50 ±0.07 ps

4293 $B \to K^\pm\pi^\mp$ cand:
τ_B = 1.51 ±0.04 ps

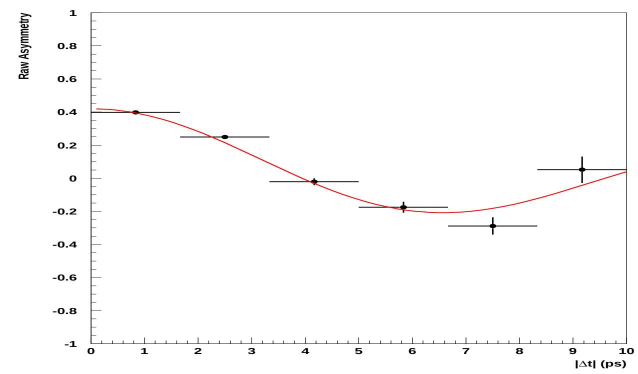
23008 $B \to D^{(*)\pm}\pi^\mp$:
τ_B = 1.559 ±0.013 ps

(PDG: τ_B = 1.536±0.014)

Cross checks III: Δm

$B \to D^{(*)\pm}\pi^{\mp}$: $\Delta m = 0.507 \pm 0.008$

$$P_{D\pi}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 - q_{\rm tag}q_{\rm rec}(1-2\omega_\ell)\cos(\Delta m\,\Delta t)\right]$$



$$P_{K^+\pi^-}(\Delta t) = \mathcal{N}_+\frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 - q_{\rm tag}\left(\frac{P-R}{P+R}\right)(1-2\omega_\ell)\cos(\Delta m\,\Delta t)\right]$$

$$P_{K^-\pi^+}(\Delta t) = \mathcal{N}_-\frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 - q_{\rm tag}\left(\frac{Q-S}{Q+S}\right)(1-2\omega_\ell)\cos(\Delta m\,\Delta t)\right]$$

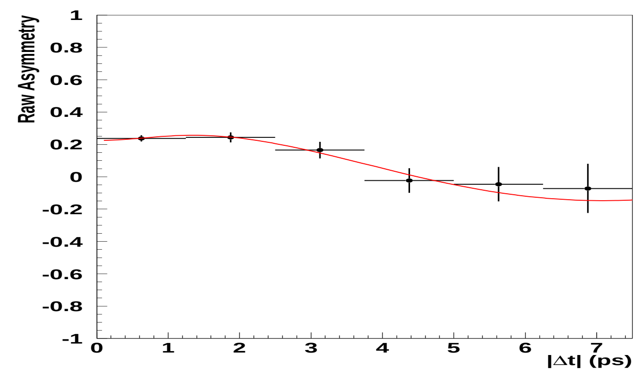
$B \to K^{\pm}\pi^{\mp}$: $\Delta m = 0.456\,^{+0.034}_{-0.030}$

$$P = \frac{1-A_{K\pi}}{2}\,\varepsilon(K^+)\,\varepsilon(\pi^-)$$

$$Q = \frac{1+A_{K\pi}}{2}\,\varepsilon(K^-)\,\varepsilon(\pi^+)$$

$$R = \frac{1+A_{K\pi}}{2}\,p(K^-\to\pi^-)\,p(\pi^+\to K^+)$$

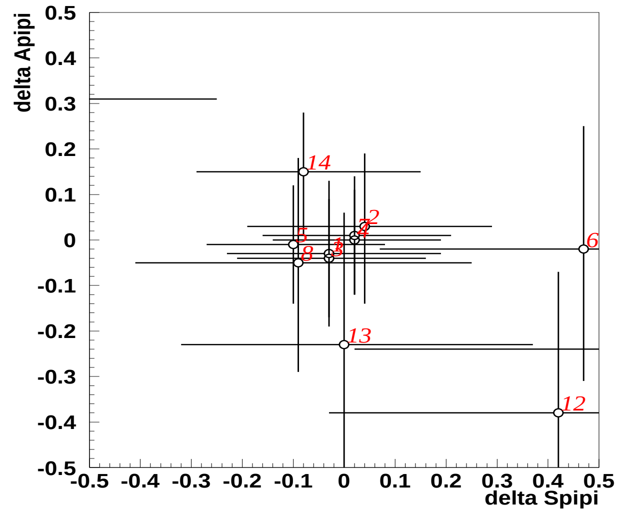
$$S = \frac{1-A_{K\pi}}{2}\,p(K^+\to\pi^+)\,p(\pi^-\to K^-)$$

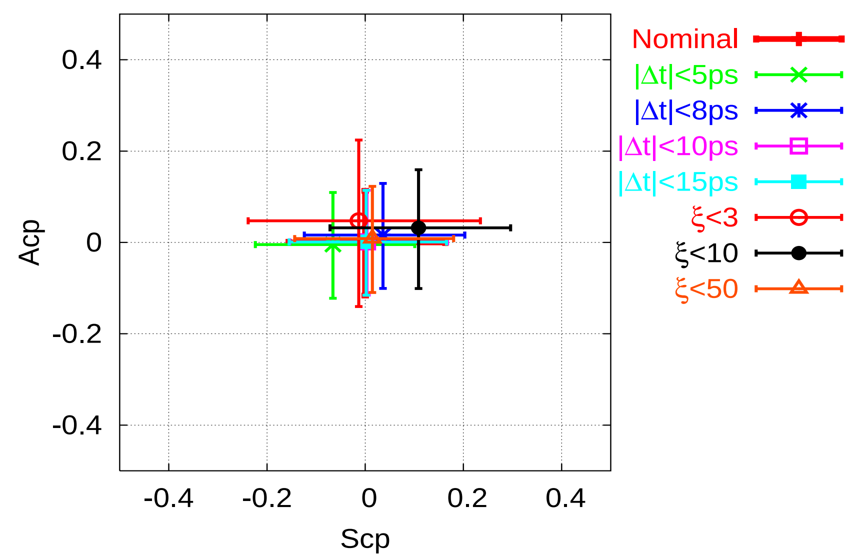


(PDG: $\Delta m = 0.502 \pm 0.007$)

Cross checks IV: subsamples

	1238	-0.03 ± 0.16	$-0.03\,^{+0.22}_{-0.20}$
$\Delta E < 0$	1582	$+0.03 \pm 0.16$	$+0.04\,^{+0.25}_{-0.23}$
$\lvert\Delta E\rvert < 1\sigma$	1189	-0.04 ± 0.13	-0.03 ± 0.18
$\lvert\Delta E\rvert < 2\sigma$	2101	$+0.00 \pm 0.11$	$+0.02 \pm 0.16$
multi tracks	2179	-0.01 ± 0.13	-0.10 ± 0.17
single track	641	$-0.02\,^{+0.27}_{-0.29}$	$+0.47 \pm 0.40$
$KLR > 0.86$	884	$+0.01 \pm 0.13$	$+0.02 \pm 0.18$
$KLR < 0.86$	1936	-0.05 ± 0.23	$-0.09\,^{+0.34}_{-0.32}$
$0 < r < 0.25$	1454	$+3.06\,^{+1.70}_{-1.72}$	-0.05 ± 2.27
$0.25 < r < 0.50$	479	$+0.31 \pm 0.53$	$-0.81\,^{+0.56}_{-0.52}$
$0.50 < r < 0.675$	254	-0.24 ± 0.42	$+0.69 \pm 0.67$
$0.675 < r < 0.75$	292	-0.38 ± 0.31	$+0.42\,^{+0.47}_{-0.45}$
$0.75 < r < 0.875$	151	-0.23 ± 0.29	$+0.00\,^{+0.37}_{-0.32}$
$0.875 < r < 1.0$	190	$+0.15 \pm 0.13$	$-0.08\,^{+0.23}_{-0.21}$



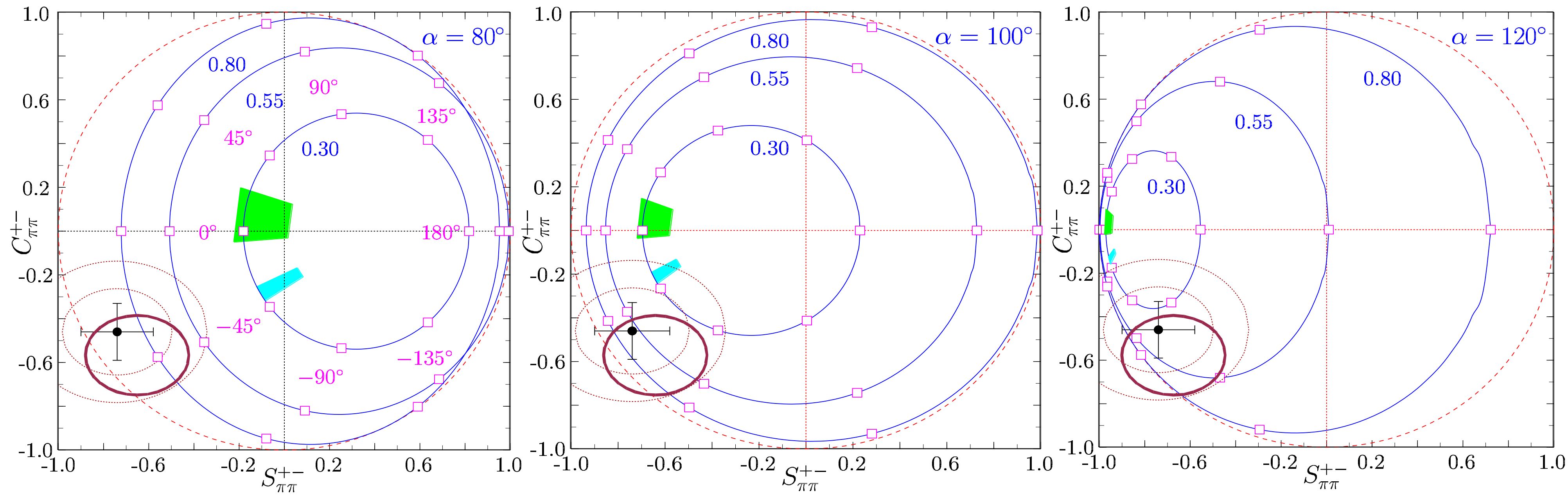


Constraints upon ϕ_2 (α) and $|P/T|$ cont'd

Ali, Lunghi, and Parkhomenko, EPJ C36, 183 (2004):

Belle (253 fb^{-1}): $C_{\pi\pi} = -0.56 \pm 0.13$, $S_{\pi\pi} = -0.67 \pm 0.17$

$\phi_2 = 80^\circ$ $\phi_2 = 100^\circ$ $\phi_2 = 120^\circ$



⇒ **small ϕ_2 requires large $|P/T|$; large $|P/T|$ allows small ϕ_2**

⇒ **small ϕ_2 requires small $|\delta|$; large ϕ_2 allows large $|\delta|$**

Constraints upon ϕ_2 (α) and |P/T| cont'd

Gronau and Rosner,
PLB 595, 339 (2004):

SU(3):

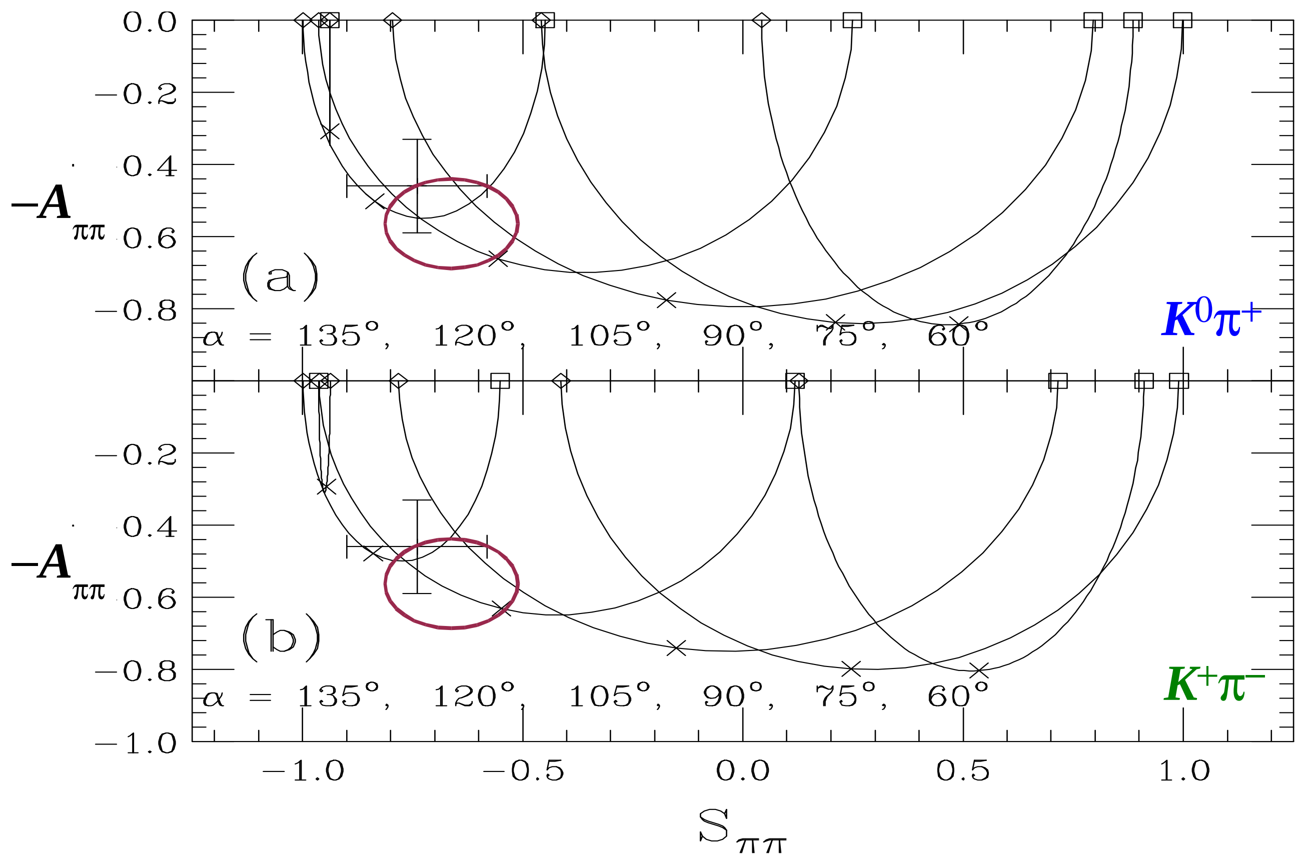
$$T_{K^+\pi^-} = \left(\frac{f_K}{f_\pi}\right)\left(\frac{V_{us}}{V_{ud}}\right) T_{\pi^+\pi^-}$$

$$P_{K^+\pi^-} = \left(\frac{V_{cs}}{V_{cd}}\right) P_{\pi^+\pi^-}$$

$$\Rightarrow \quad \frac{\Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^0 \to \pi^+\pi^-)} \text{ or } \frac{\Gamma(B^+ \to K^0\pi^+)}{\Gamma(B^0 \to \pi^+\pi^-)}$$

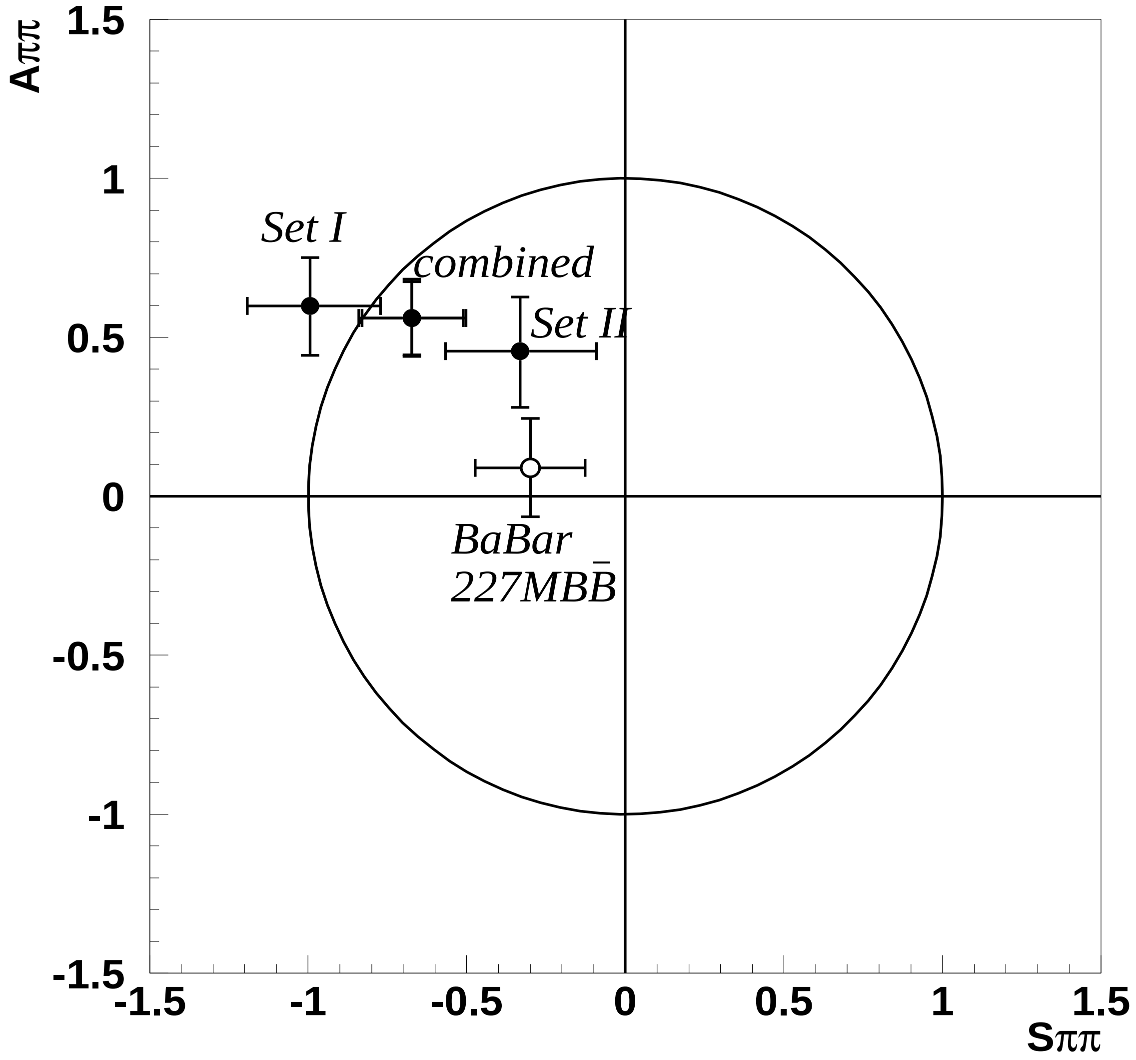
provides the needed constraint

⇒ ϕ_2 about 100° is favored



Note: this paper uses *SU*(3) symmetry to predict $A_{\pi\pi} = -3\,A_{K\pi}$ which is correct to 2σ ($A_{K\pi}$ = −0.109 +− 0.019)

Compare with previous result & BaBar



CL = 4% for difference of two Belle datasets (not including systematic errors)

2.3σ difference between Belle and BaBar