Angles of the CKM unitarity triangle measured at Belle

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- **Introduction**
- **Determining sin(2ϕ_1) (β)**
- **Determining sin(2ϕ_2) (α)**
- **Determining ϕ_3 (γ)**
- **Summary**

Introduction I

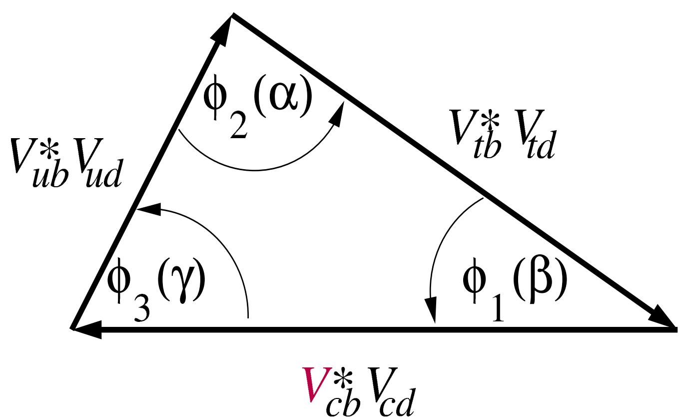
CKM weak mixing matrix:

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$U^\dagger U = 1 \quad \Rightarrow$$

$$\begin{aligned} V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} &= 0 \\ V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} &= 0 \\ V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} &= 0 \end{aligned}$$

$$\begin{aligned} V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} &= 0 \\ V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} &= 0 \\ V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} &= 0 \end{aligned}$$

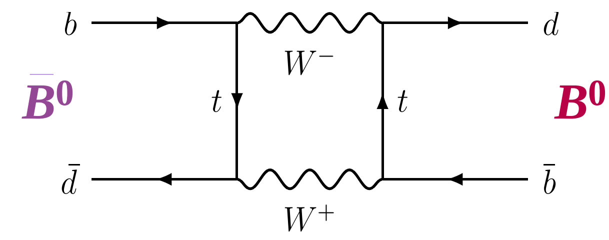


$$\begin{aligned} \phi_1\ (\beta) &= \arg\left(\frac{V_{cb}^* V_{cd}}{-V_{tb}^* V_{td}}\right) \\ \phi_2\ (\alpha) &= \arg\left(\frac{V_{tb}^* V_{td}}{-V_{ub}^* V_{ud}}\right) \\ \phi_3\ (\gamma) &= \arg\left(\frac{V_{ub}^* V_{ud}}{-V_{cb}^* V_{cd}}\right) \end{aligned}$$

Does the triangle close? *i.e.*, are there >3 generations?

Introduction II (some formalism)

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



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

$$|B^0(t)\rangle = e^{-(\Gamma/2+i\bar{m})\,t}\left[\cos\left(\frac{\Delta m}{2}t\right)|B^0\rangle + \left(\frac{q}{p}\right) i\sin\left(\frac{\Delta m}{2}t\right)|\bar{B}^0\rangle\right]$$
$$|\bar{B}^0(t)\rangle = e^{-(\Gamma/2+i\bar{m})\,t}\left[\left(\frac{p}{q}\right) i\sin\left(\frac{\Delta m}{2}t\right)|B^0\rangle + \cos\left(\frac{\Delta m}{2}t\right)|\bar{B}^0\rangle\right],$$

$$|\langle f|H|B^0(t)\rangle|^2 = \frac{|\mathcal{A}_f|^2 e^{-\Gamma t}}{2}\left[1 + |\lambda|^2 + (1-|\lambda|^2)\cos(\Delta m t) - 2\,\mathrm{Im}\,\lambda\ \sin(\Delta m t)\right]$$
$$|\langle f|H|\bar{B}^0(t)\rangle|^2 = \frac{|\mathcal{A}_f|^2 e^{-\Gamma t}}{2}\left[1 + |\lambda|^2 - \left(1-|\lambda|^2\right)\cos(\Delta m t) + 2\,\mathrm{Im}\lambda\ \sin(\Delta m t)\right]$$

$$\lambda = \left(\frac{q}{p}\right)\frac{A(\overline{B}^0 \to f)}{A(B^0 \to f)} = e^{i2\phi_1}\,e^{i2\phi} \qquad \text{(one weak phase)}$$

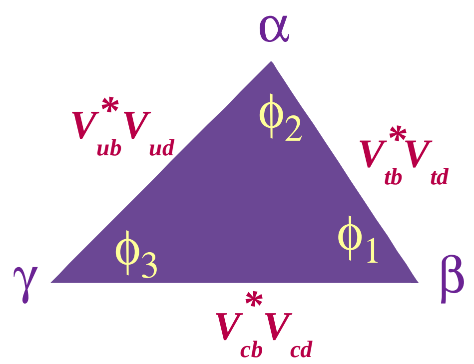
Introduction III

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

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

$$\lambda = \left(\frac{q}{p}\right)\frac{A(\overline{B}^0\to f)}{A(B^0\to f)} = e^{i2\phi_1}\,e^{i2\phi} \qquad \text{(one weak phase)}$$

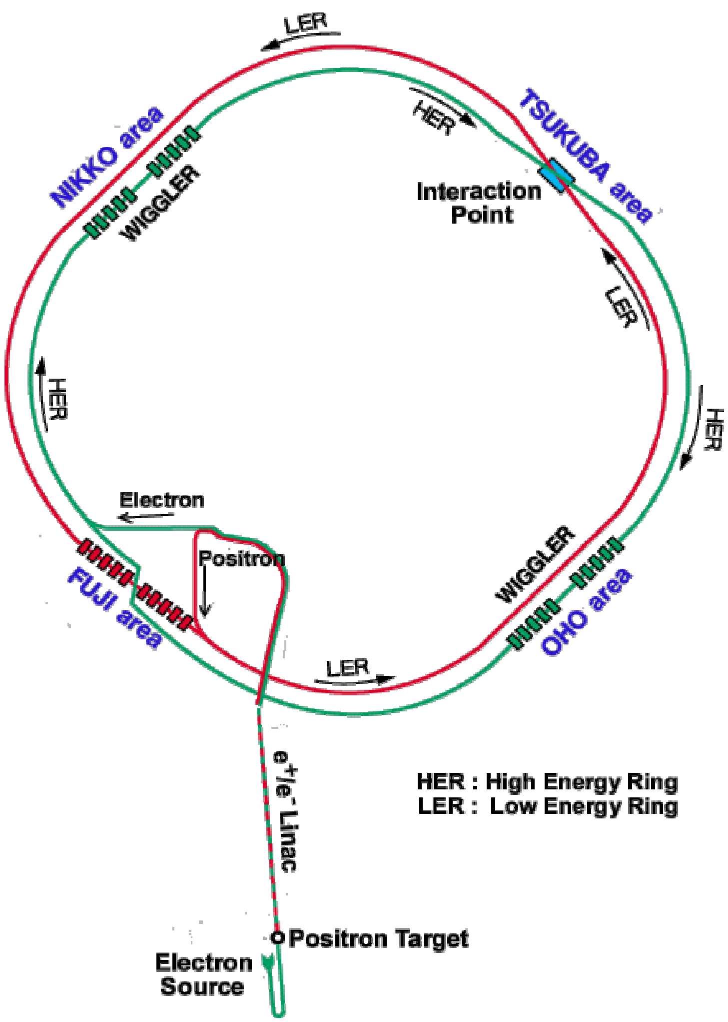
$$\Rightarrow\ \mathcal{A}_f \approx 0, \qquad \mathcal{S}_f \approx \sin 2(\phi_1+\phi) = -\sin 2\phi'$$

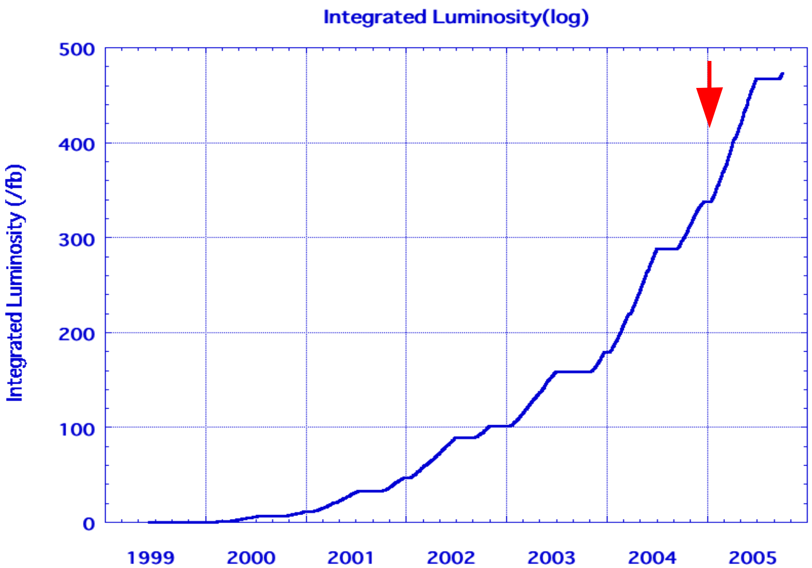


Belle at KEKB

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

3.5 GeV on 8.0 GeV



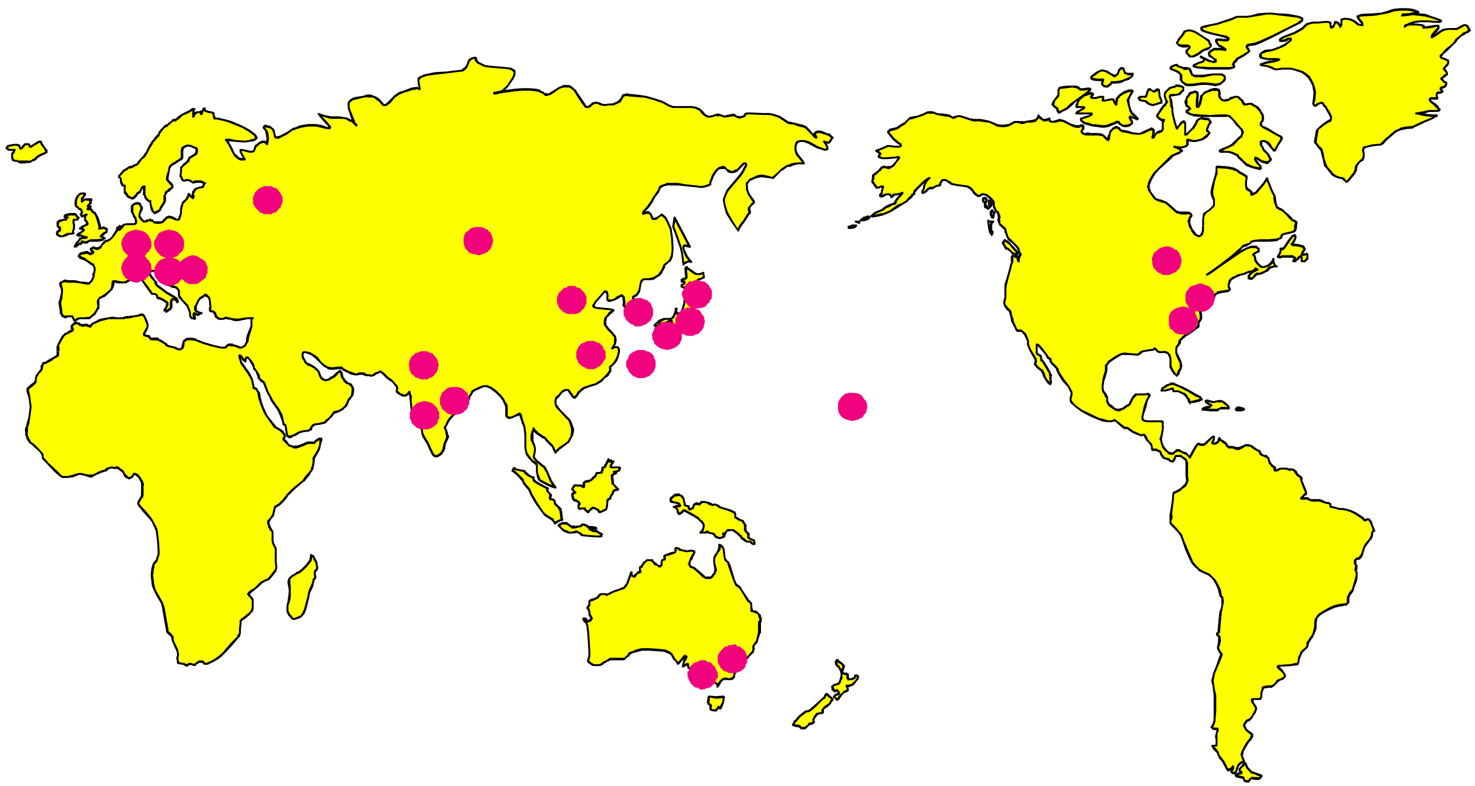


$\int L\,dt = 476\ fb^{-1}$ on 4 Oct 2005

L_{peak} (max) = $1.6 \times 10^{34}\ cm^{-2}\ s^{-1}$

357 fb^{-1} on resonance (386M *BB*) analyzed thus far

The Belle Collaboration

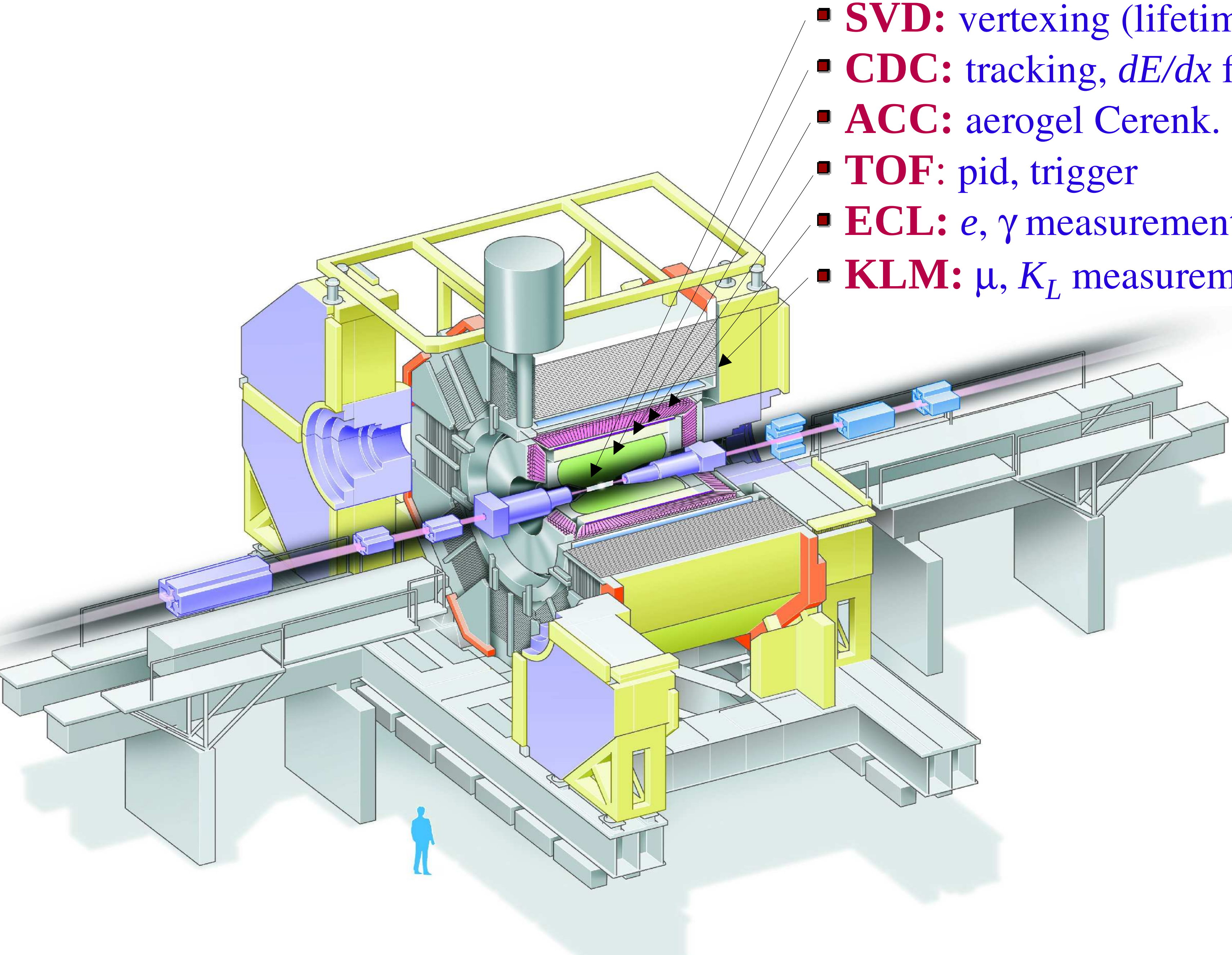


About 400 people from 59 institutions, many nations

US: Cincinnati
Hawaii
Princeton
Virginia Tech

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:

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

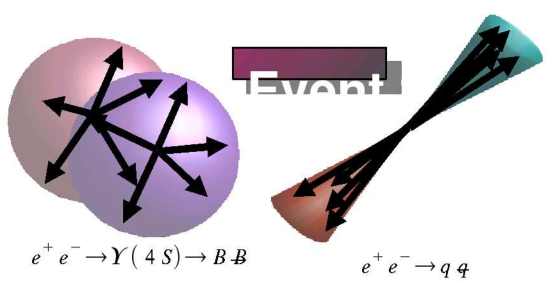
$$\Delta E = E^*_B - E^*_{beam}$$

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

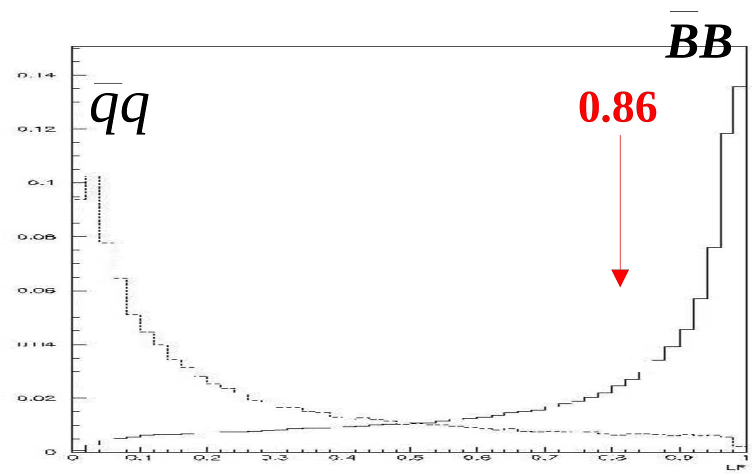
2) Flavor tagging:

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

3) Continuum suppression:



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



KLR

4) Vertexing and Δt fit

Measurement of sin(2ϕ_1) with $B^0 \to J/\psi\, K^0$

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

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

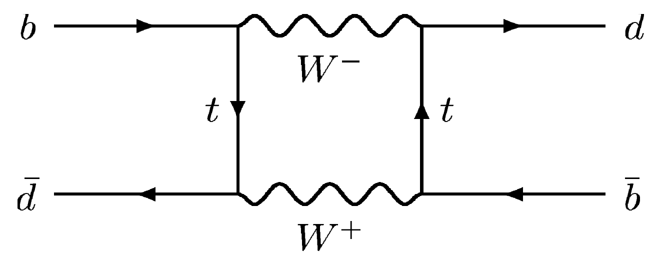
$$= -\frac{-V_{cb}V_{cd}^*/(V_{td}^*V_{tb})}{-V_{cb}^*V_{cd}/(V_{td}V_{tb}^*)}$$

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

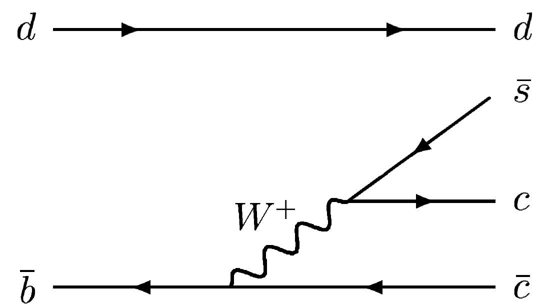
$$= -e^{-2i\phi_1}$$

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

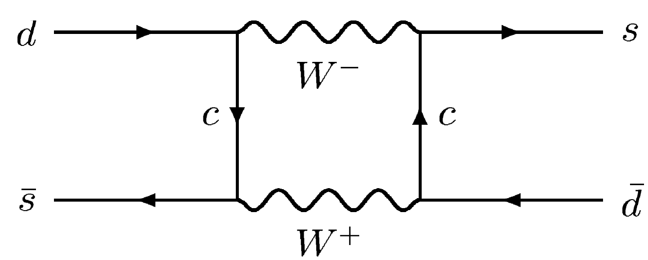
$\bar{B}^0$-B^0 oscillation:



Tree:

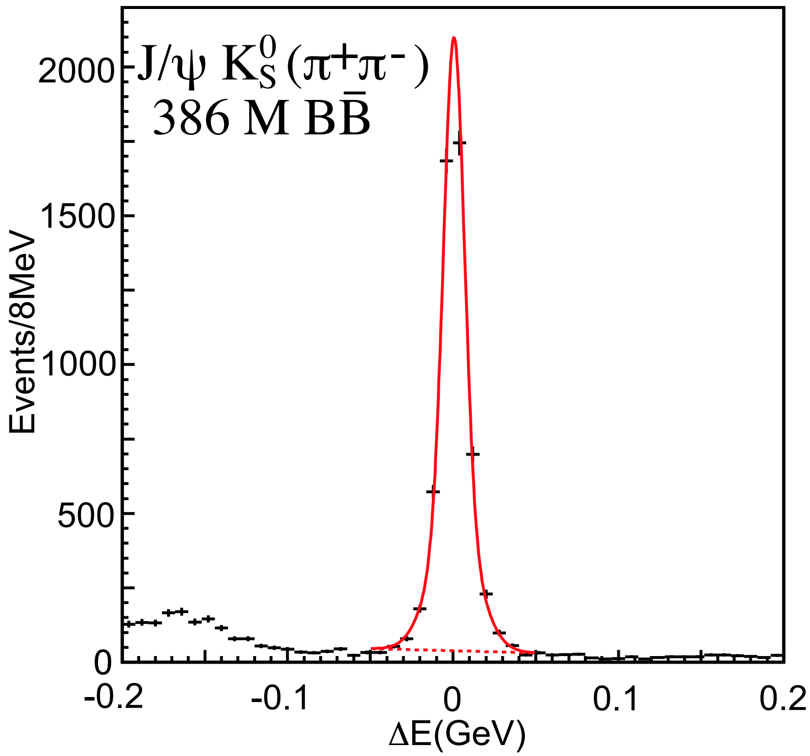


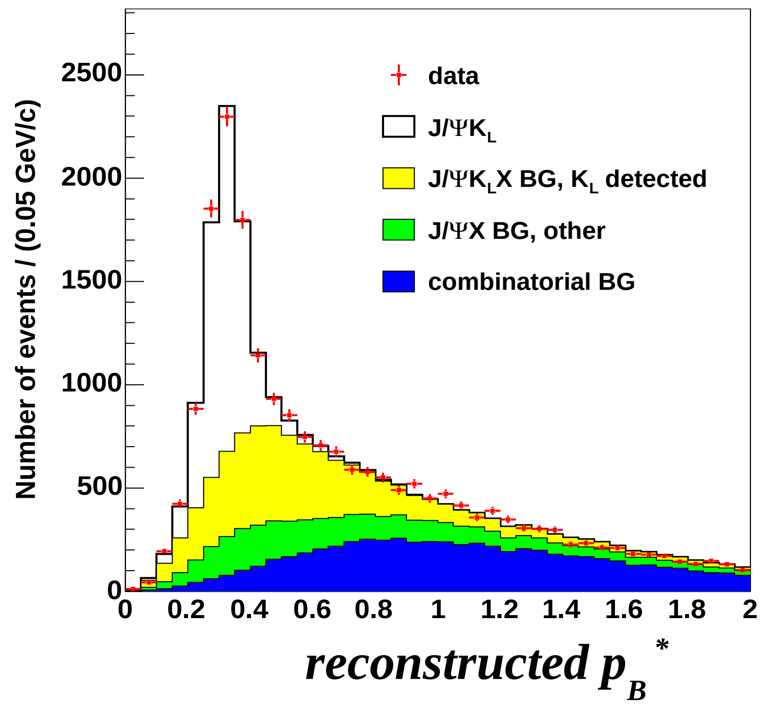
$\bar{K}^0$-K^0 oscillation:



Measurement of sin(2ϕ_1) with b→ccs (hep-ex/0507037)

357 fb $^{-1}$:



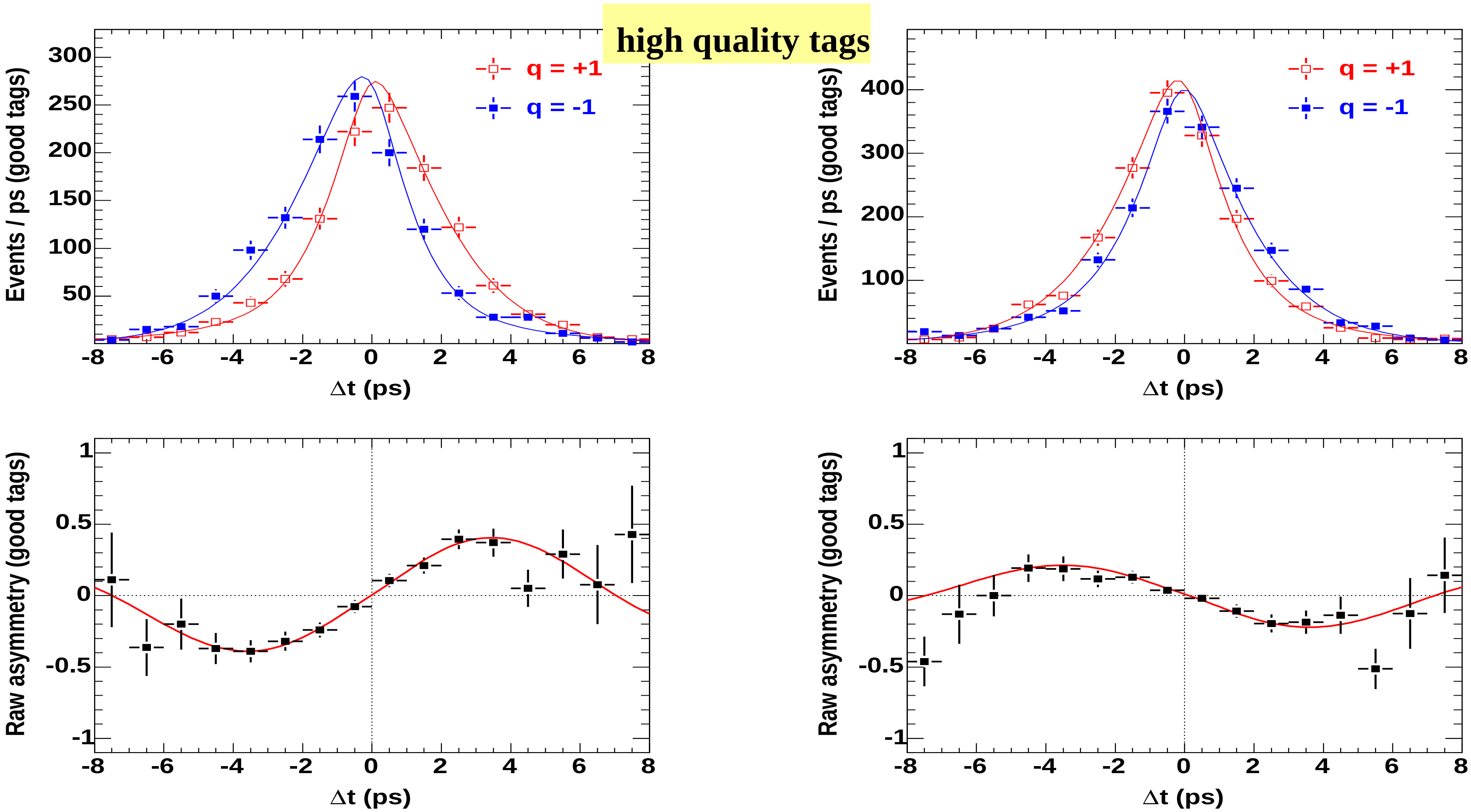


$B^0 \rightarrow J/\psi\, K_S$ (CP = −1)
5264 events
98% pure

$B^0 \rightarrow J/\psi\, K_L$ (CP = +1)
4792 events
60% pure

Note: cannot use Δ*E* because we don't have E_{KL}

Measurement of $\sin(2\phi_1)$ with $b\to c\bar{c}s$ (hep-ex/0507037)



$\sin(2\phi_1) = 0.652 \pm 0.039 \pm 0.020$

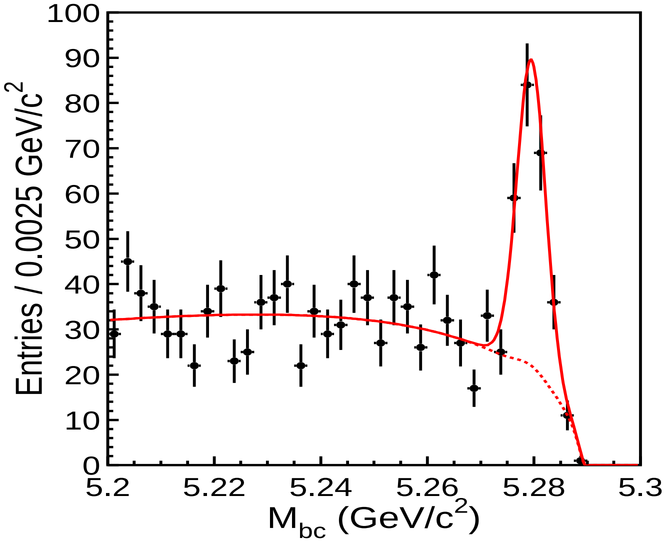
$\Rightarrow \quad \phi_1 = (20.3\,^{+1.7}_{-1.6})^{o}$

close to BaBar 210 fb^{-1}:

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

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

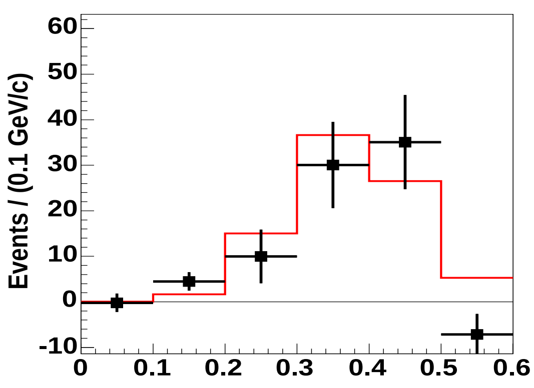
Measurement of $\sin(2\phi_1)$ with $b\rightarrow sss$ (hep-ex/0507037)



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

$N = 180 \pm 16$

57% pure



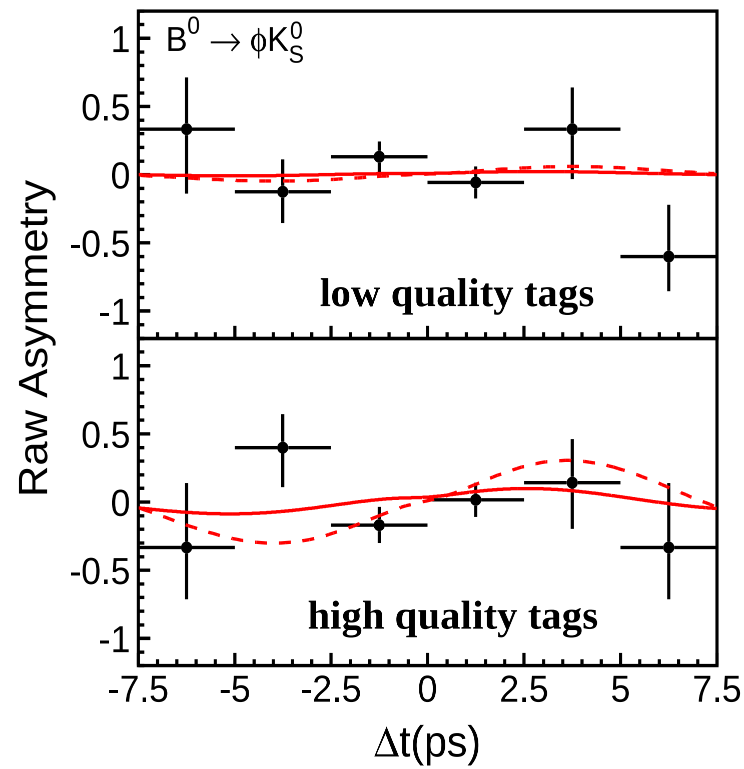
reconstructed p_B^*

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

$N = 78 \pm 13$

12% pure

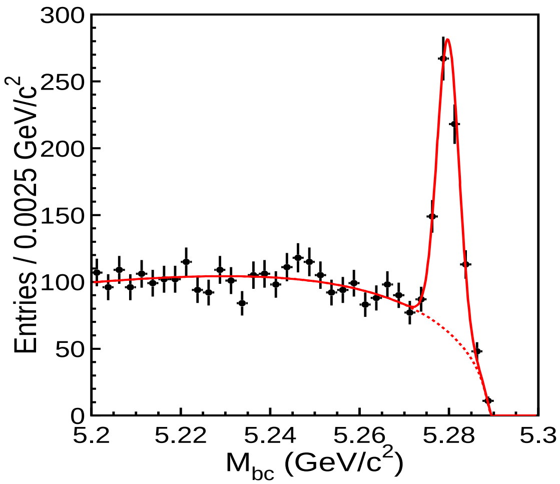
$B^0 \rightarrow \phi K^0_S$:



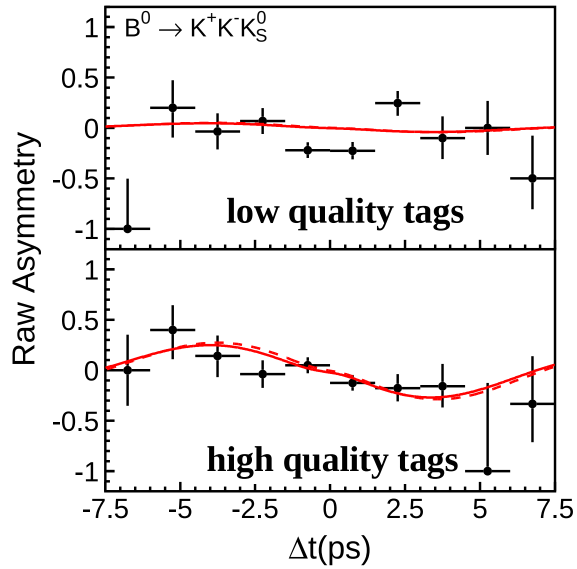
$\sin(2\phi_1) = +\,0.44 \pm 0.27 \pm 0.05$

$A = +\,0.14 \pm 0.17 \pm 0.07$

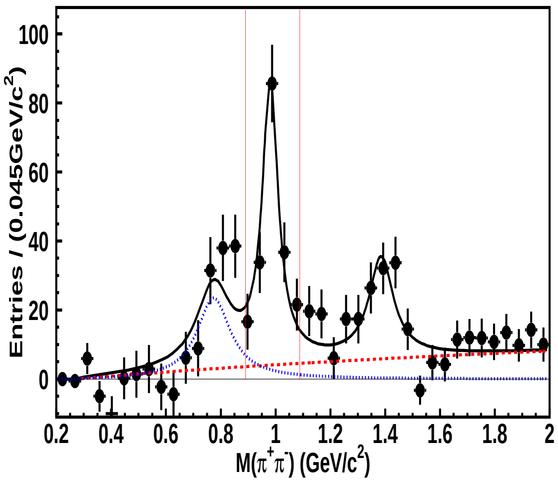
Measurement of $\sin(2\phi_1)$ with $b \to qqs$ (hep-ex/0507037)



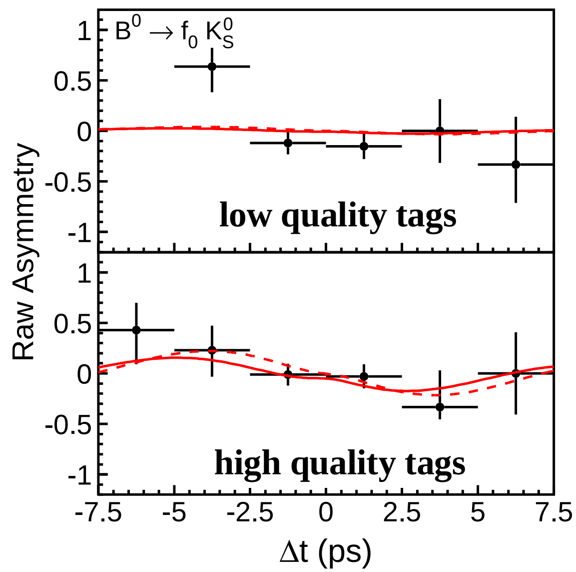
$B^0 \to K^+K^-K_S$
(CP = +1 mostly)
$N = 536 \pm 29$
55% pure



$\sin(2\phi_1) =$
$-0.52 \pm 0.16 \pm 0.03$
$A =$
$-0.06 \pm 0.11 \pm 0.07$

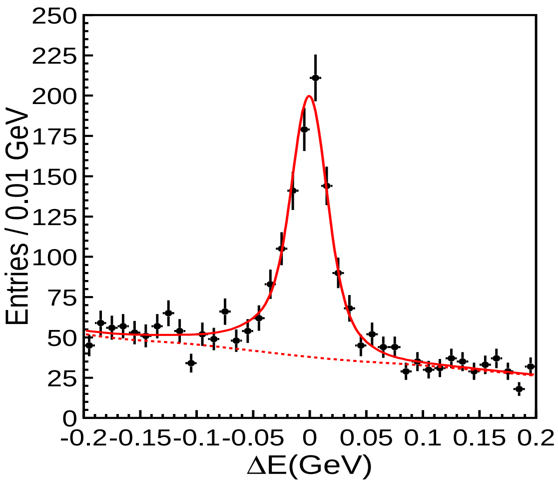


$B^0 \to f_0(980)K_S$
(CP = +1)
$N = 145 \pm 16$
47% pure

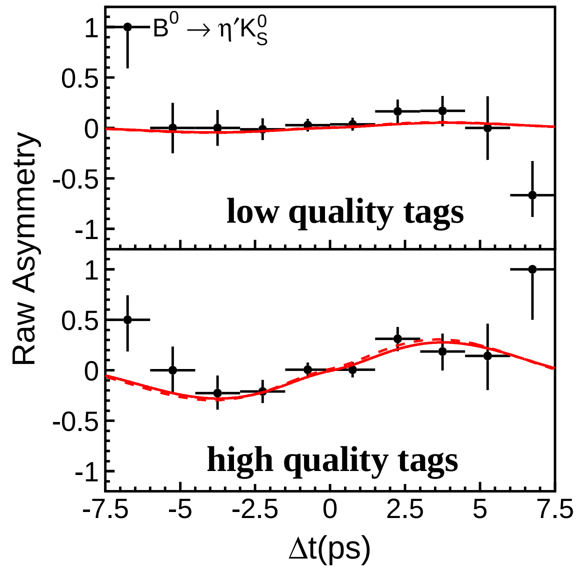


$\sin(2\phi_1) =$
$-0.47 \pm 0.36 \pm 0.08$
$A =$
$-0.23 \pm 0.23 \pm 0.13$

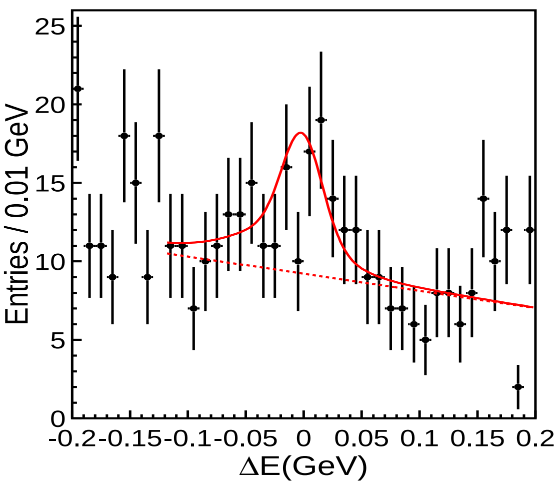
Measurement of $\sin(2\phi_1)$ with $b\to qqs$ (hep-ex/0507037)



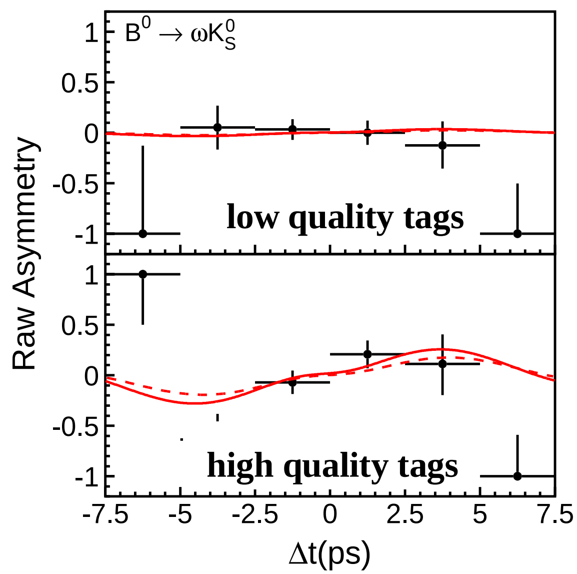
$B^0 \to \eta' K_s$
(CP = –1)
N = 512 ±27
61% pure



$\sin(2\phi_1)$ =
+ 0.65 ±0.18±0.04
A =
– 0.19 ±0.11±0.05

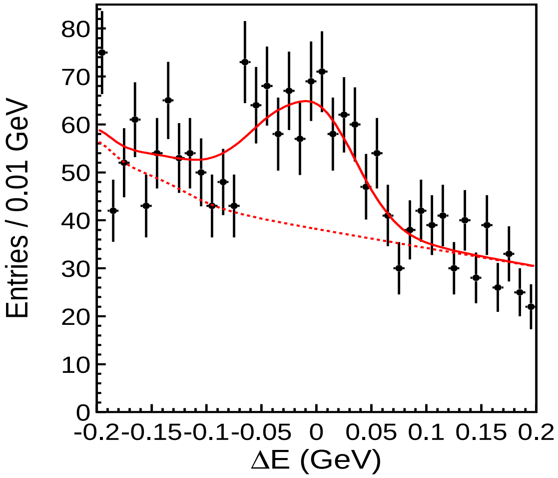


$B^0 \to \omega K_s$
(CP = –1)
N = 31 ±7
56% pure

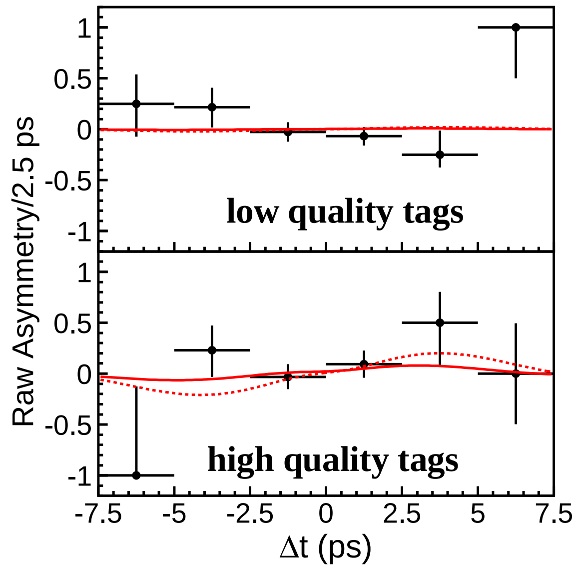


$\sin(2\phi_1)$ =
$+ 0.75 \pm 0.64 ^{+0.13}_{+0.16}$
A =
+ 0.26 ±0.48±0.15

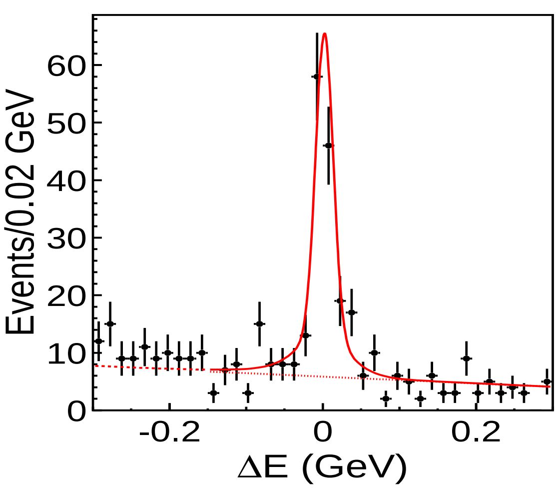
Measurement of sin(2ϕ_1) with $b \to qqs$ (hep-ex/0507037)



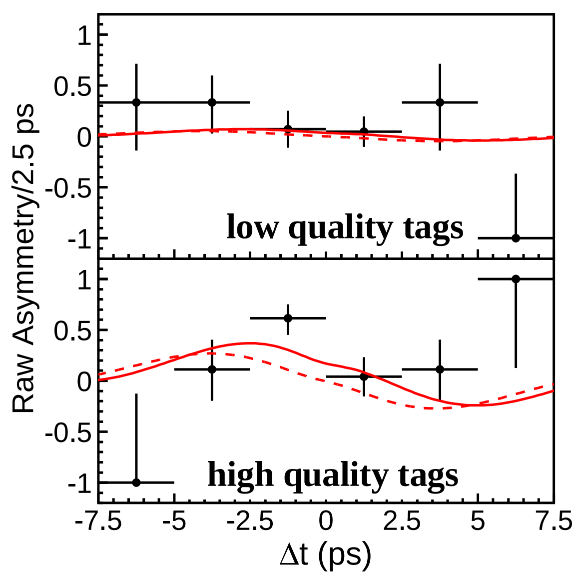
$B^0 \to \pi^0 K_S$
(*CP* = −1)
***N* = 344 ±30**
25% pure



sin(2ϕ_1) =
+ 0.22 ±0.47±0.08
***A* =**
+ 0.11 ±0.18±0.08

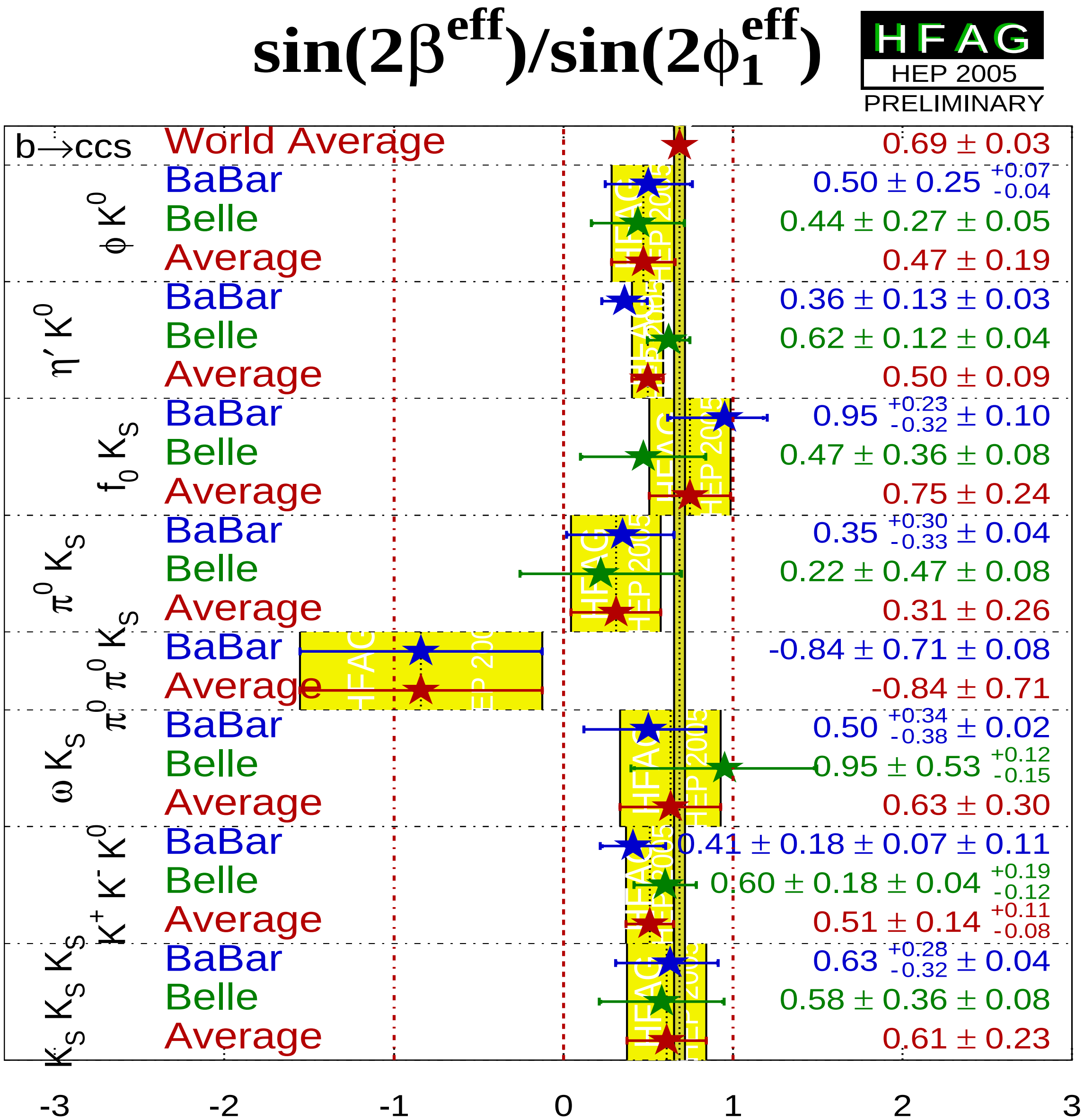


$B^0 \to K_S K_S K_S$
(*CP* = +1)
***N* = 105 ±12**
64% pure



sin(2ϕ_1) =
− 0.58 ±0.36±0.08
***A* =**
+ 0.50 ±0.23±0.06

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



⇒ **modulu final-state interactions (see Soni, hep-ph/0502235), results appear consistent with SM**

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

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

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

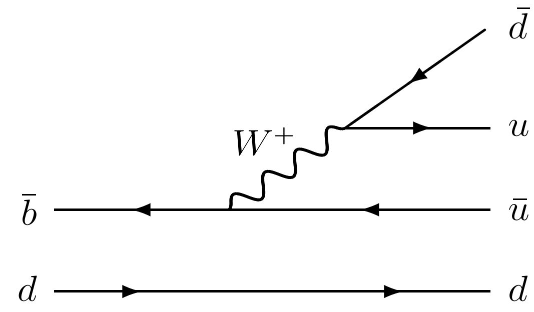
$$= \frac{|\mathcal{M}'|e^{i\phi_2}}{|\mathcal{M}'|e^{-i\phi_2}}$$

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

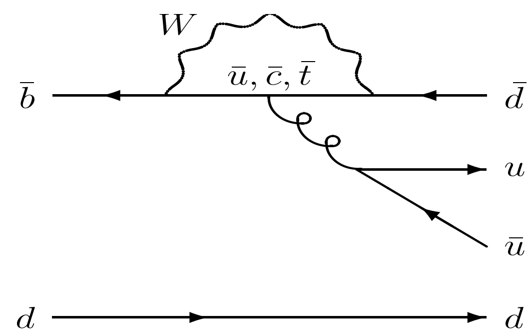
$$\Rightarrow \quad \mathcal{A}_{\pi\pi} = 0 \qquad \mathcal{S}_{\pi\pi} = \sin(2\phi_2)$$

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

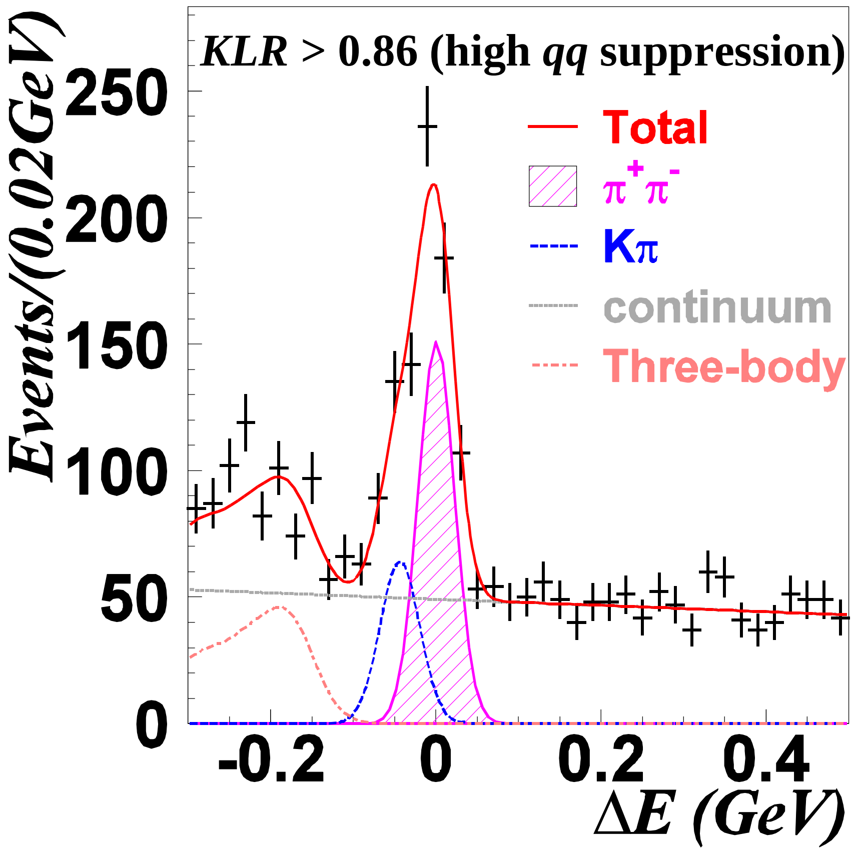
Tree:

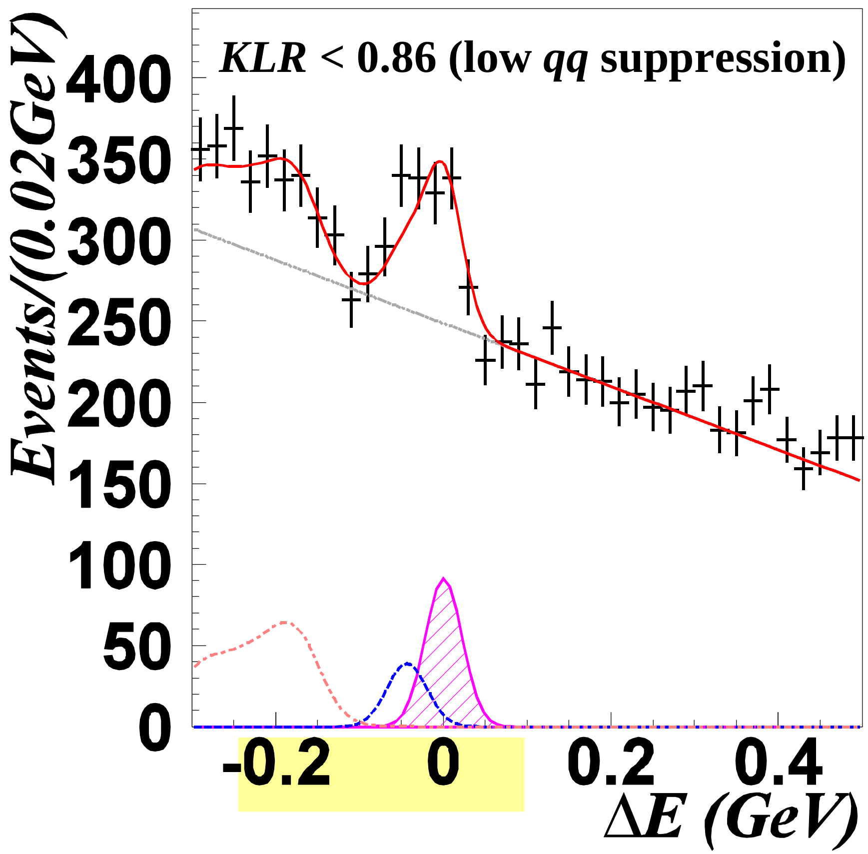


Penguin:



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





$N_{\pi\pi}$ = 415 ±13

$N_{\pi\pi}$ = 251 ±8

Maximum likelihood fit to Δt ($B^0 \to \pi^+\pi^-$)

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

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

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

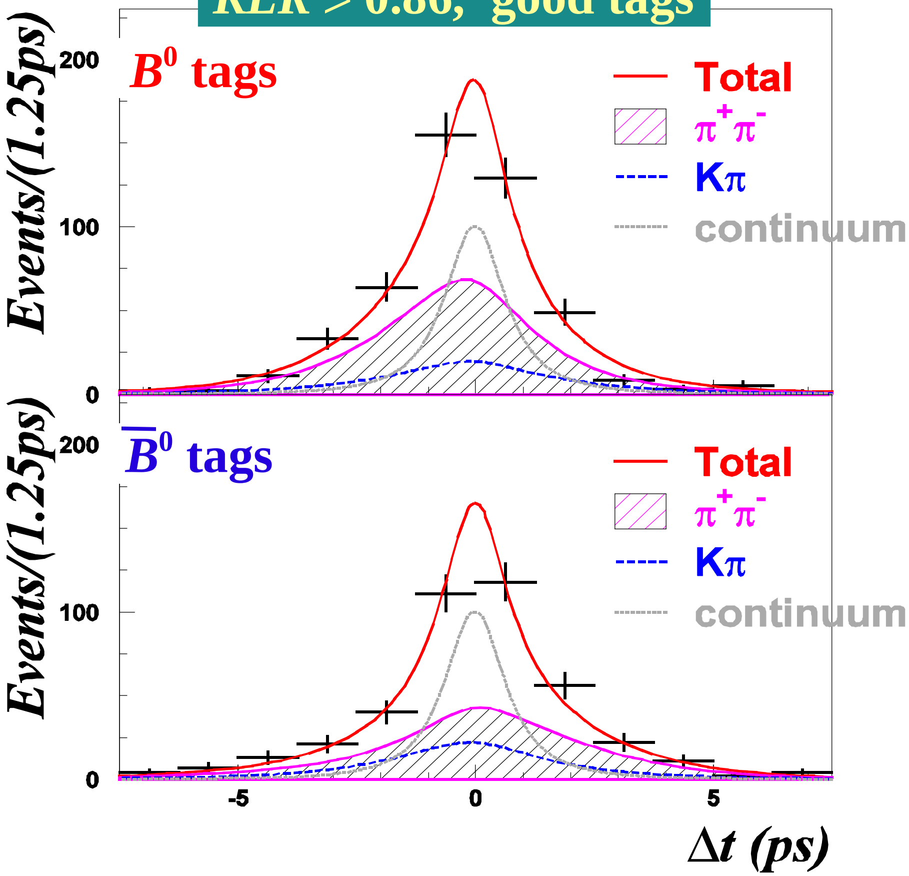
$$P_{q\bar{q}} = f\,\frac{e^{-|\Delta t|/\tau_{q\bar{q}}}}{2\tau_{q\bar{q}}} + (1-f)\,\delta(\Delta t)\,,$$

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

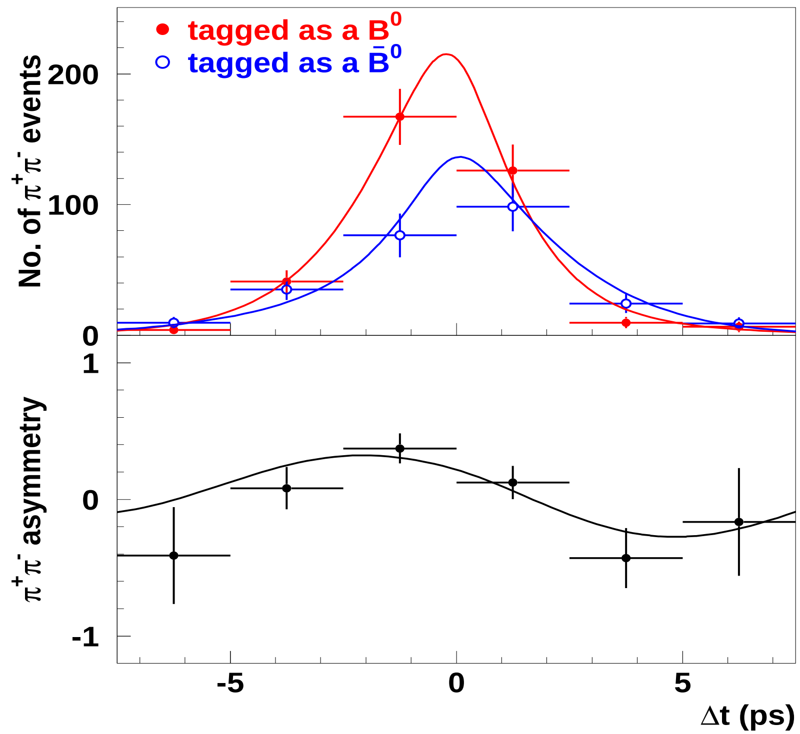
Results of Fit

(hep-ex/0502035)

KLR > 0.86, good tags



m_{bc}-Δ*E* 2D fit for event yields in bins of Δ*t* :



$$A_{\pi\pi} = 0.56^{+0.11}_{-0.12} \qquad S_{\pi\pi} = -0.67 \pm 0.16$$

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

← **includes uncertainty in final state radiation** (Background fractions)

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

Constraints upon ϕ_2 (α) and |P/T|

Gronau and Rosner,
PRD 65, 093012, 2002:

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

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

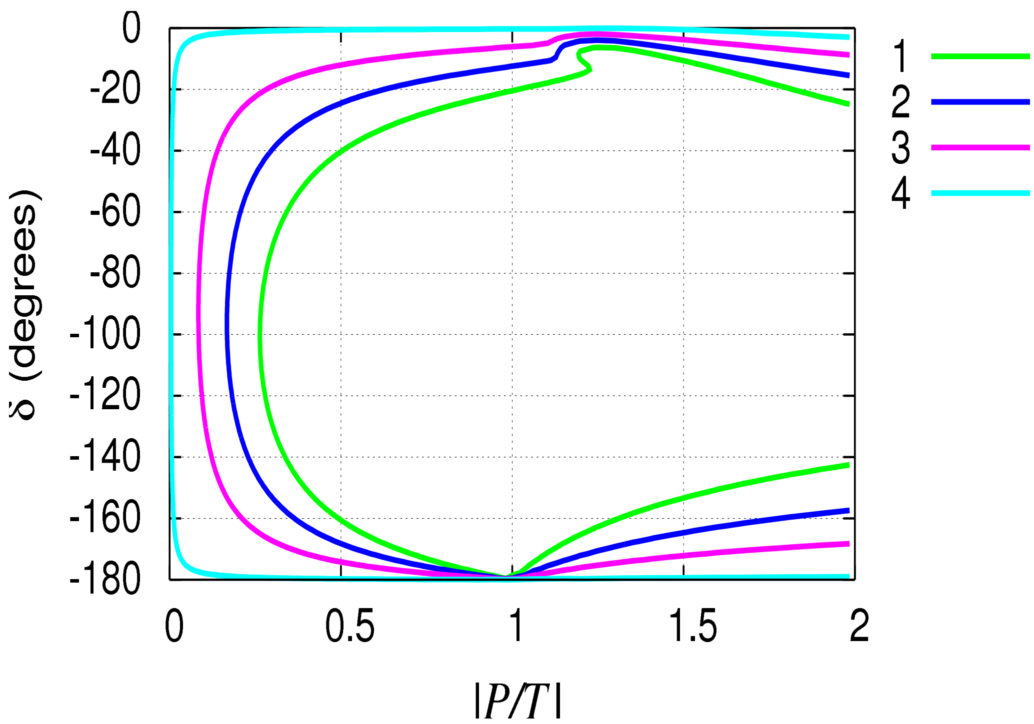
$$(\delta \equiv \delta_P - \delta_T)$$

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

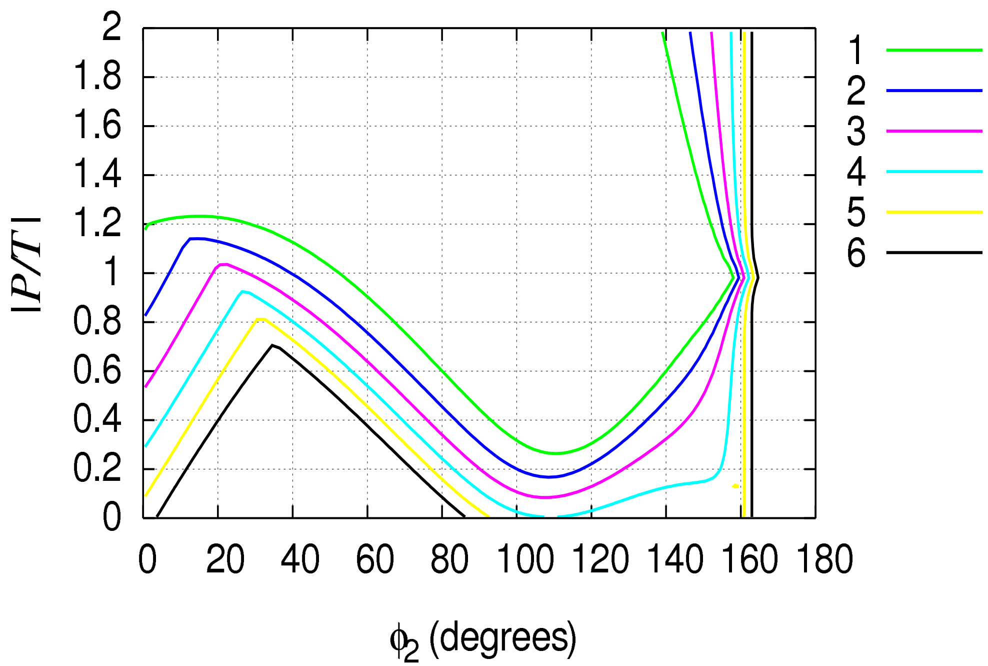
$$A_{\pi\pi} \equiv \frac{|\lambda|^2-1}{|\lambda|^2+1} = \frac{-2|P/T|\sin(\phi_1+\phi_2)\sin\delta}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

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

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

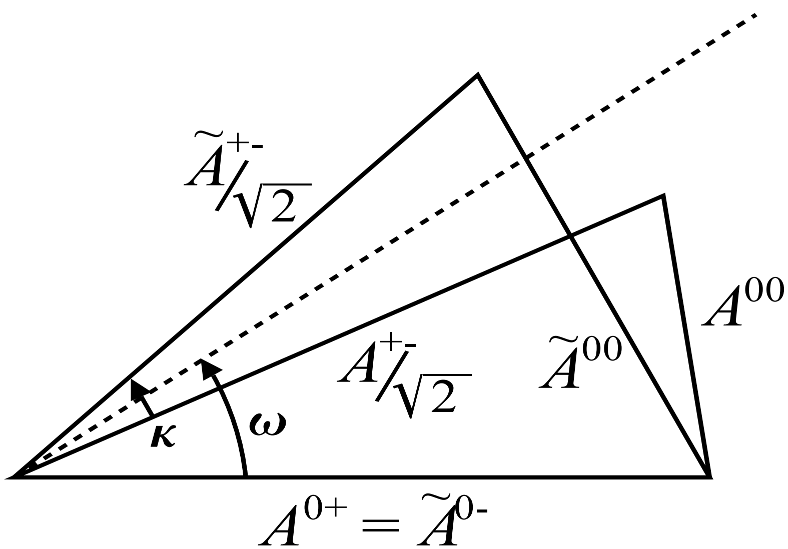
***SU(2)* isospin analysis:**

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



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

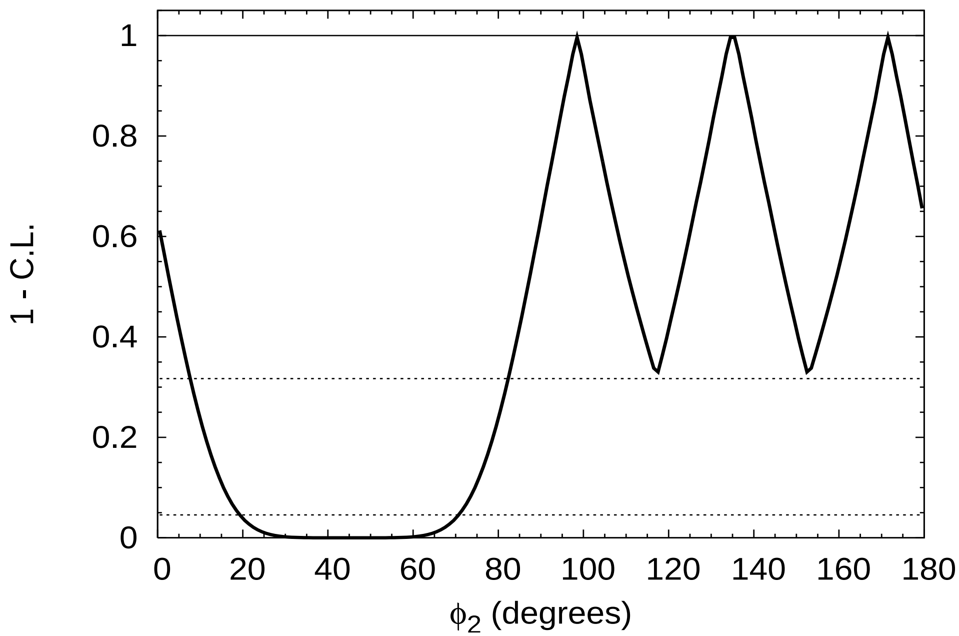
Isospin analysis for ϕ_2 cont'd

(hep-ex/0502035)

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

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)

sin(2ϕ_2) with $B^0 \to \rho^+\rho^-$

First results: 253 fb-1
(hep-ex/0507039)

Advantages:

- *CP* = +1 like $\pi^+\pi^-$
- "large" branching fraction (> 20 x 10^{-6})
- branching fraction for $B^0 \to \rho^0\rho^0 < 1.1 \times 10^{-6}$

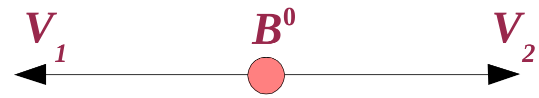
  ⇒ **small penguin amplitude**

  ⇒ $A_{\rho\rho} = 0$ and $S_{\rho\rho} = \sin(2\phi_2)$

But complications:

- different polarization ⇒ different *CP* states
- nonresonant contribution
- possible isospin *I* =1 contribution

$B^0 \to VV$ polarization

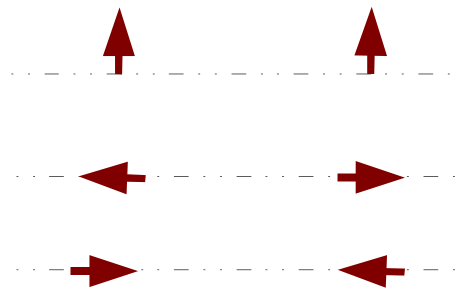


Helicity basis:

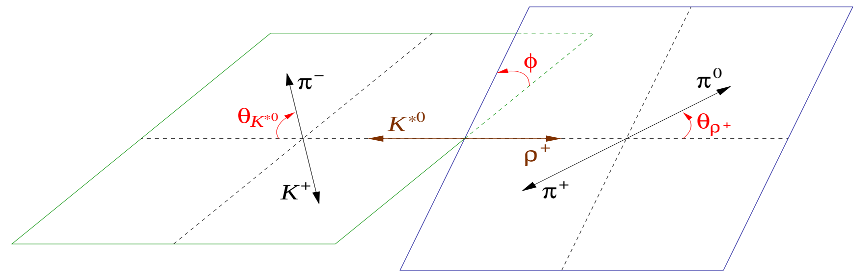
A_0

A_{+1}

A_{-1}



Variables θ_1, θ_2, ϕ :

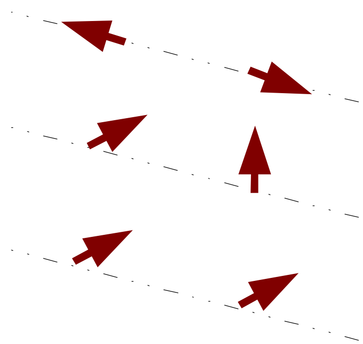


Transversity basis:

A_0

$A_\perp$

$A_\parallel$

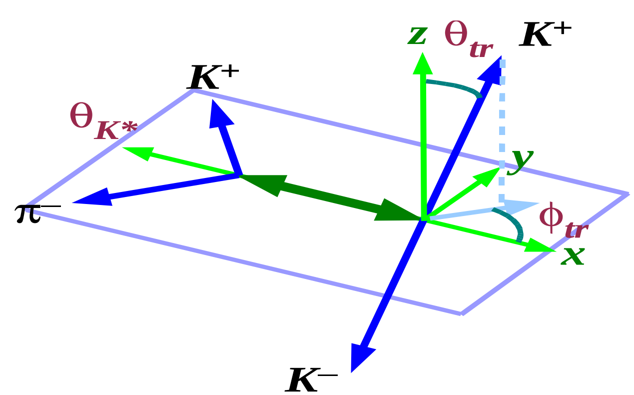


CP = +1

CP = −1

CP = +1

Variables θ_K, θ_{tr}, ϕ_{tr} :



Factorization:

$$f_L \equiv \frac{|A_0|^2}{|A_0|^2 + |A_{+1}|^2 + |A_{-1}|^2} = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \approx 1 - O\left(\frac{m_V^2}{m_B^2}\right) \approx 1$$

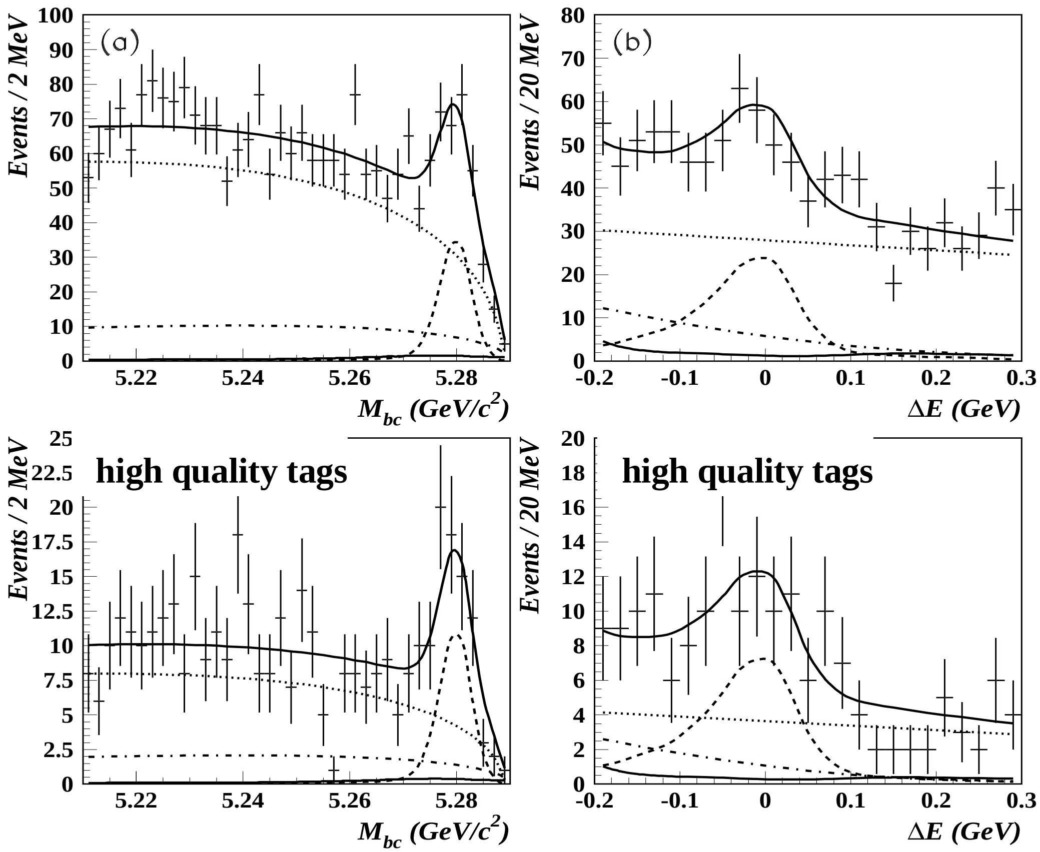
Kagan, PLB 601, 151 (2004)

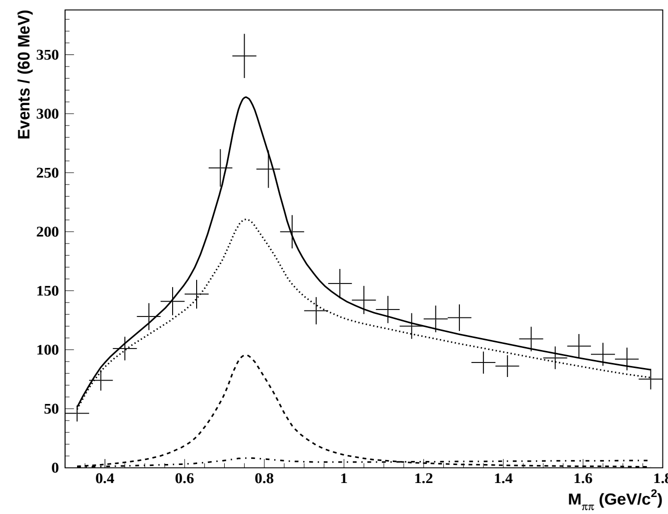
$\sin(2\phi_2)$ with $B^0 \to \rho^+\rho^-$ (cont'd)

253 fb^{-1} :

$0.62 < m_{\pi\pi} < 0.92$ GeV/c^2

$-0.10 < \Delta E < 0.06$ GeV $\qquad$ $5.273 < m_{bc} < 5.290$ GeV/c^2



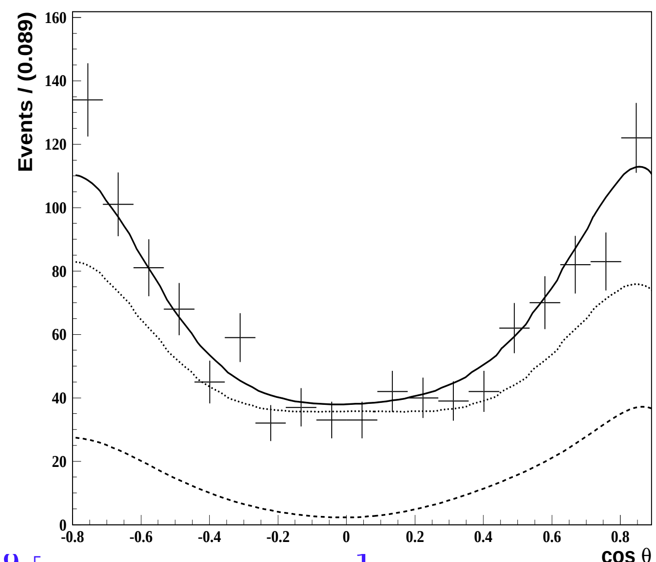


$f_{\rho\pi\pi} = (8.9 \pm 6.2)$ %

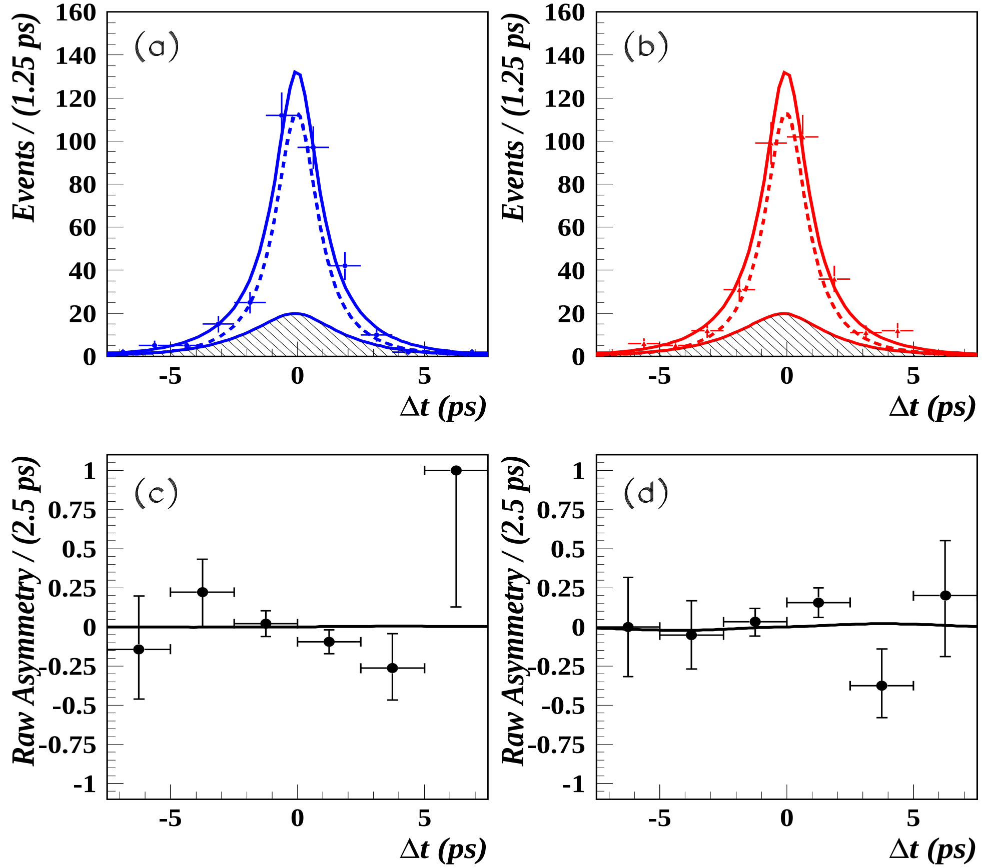
$N_{\rho\rho} = 142 \pm 13$

$\sin(2\phi_2)$ with $B^0 \to \rho^+\rho^-$ (cont'd)

253 fb^{-1} :



$$\frac{9}{4}\left[f_L \cos^2\theta_1 \cos^2\theta_2 \; + \; \frac{1}{4}(1-f_L)\sin^2\theta_1 \sin^2\theta_2 \right]$$



$f_L = (95.1 +3.3 - 3.9 \pm 3.0)$ %

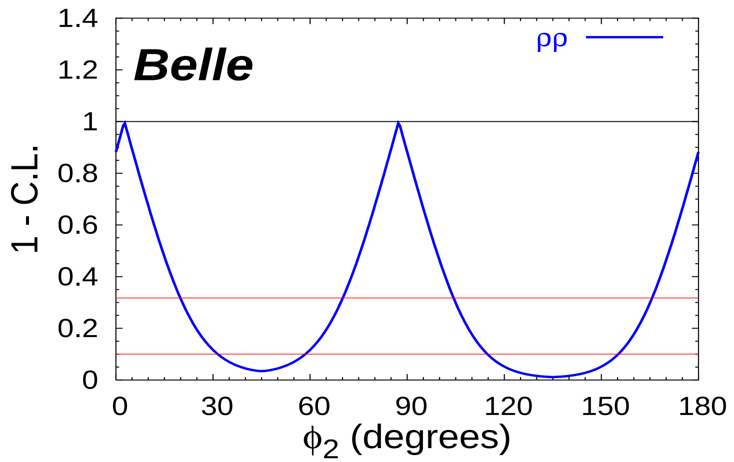
$A_{\rho\rho} = 0.00 \pm 0.30 \, ^{+0.10}_{-0.09}$

$S_{\rho\rho} = 0.09 \pm 0.42 \pm 0.08$

no *CPV*

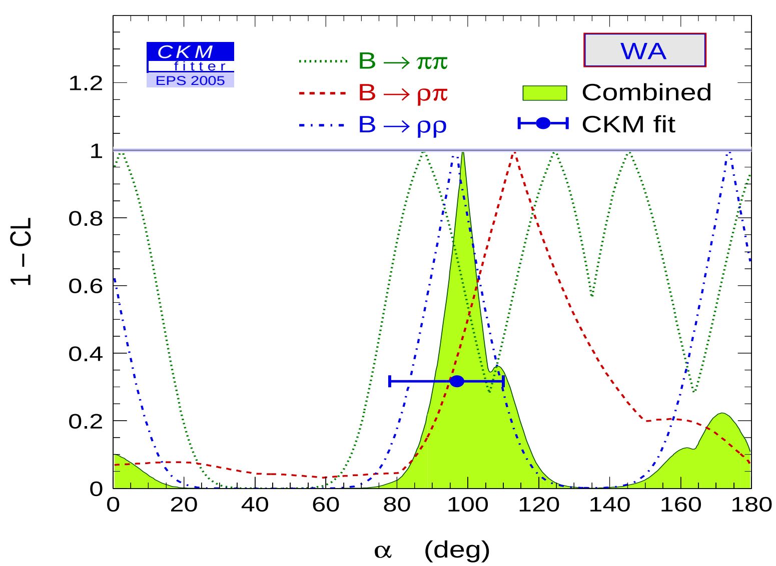
$\sin(2\phi_2)$ with $B^0 \to \rho^+\rho^-$ (cont'd)

253 fb^{-1} :



$\phi_2 = (87 \pm 17)^o$

$59^o < \phi_2 < 115^o$ (90% CL)



(http://ckmfitter.in2p3.fr)

CKM fitter

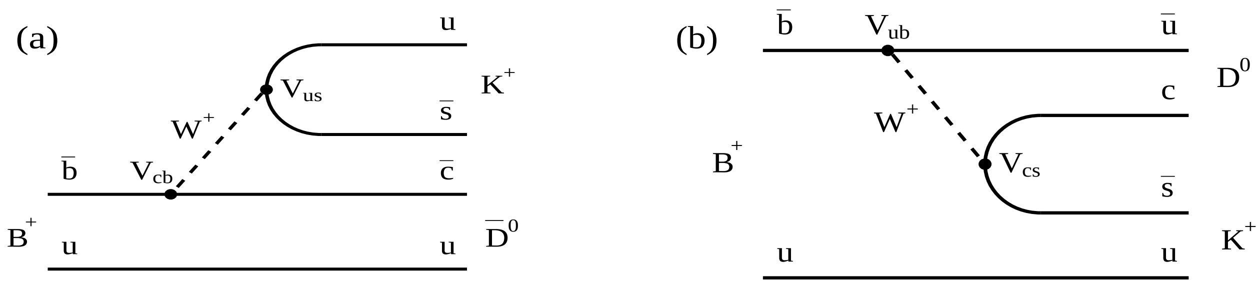
Belle + BaBar:

$\phi_2 = (96 \pm 13)^o$

Measurement of ϕ_3

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

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



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

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

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

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

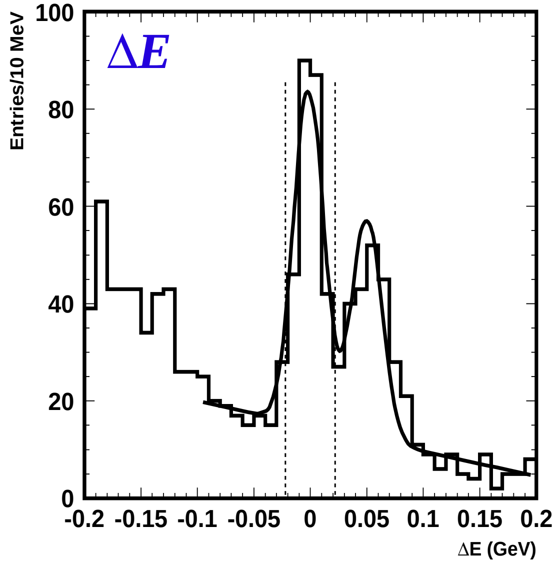
$$|M_\pm|^2 = (r^2)_- \left|A(m_+^2,\,m_-^2)\right|^2 + (r^2)_+ \left|A(m_-^2,\,m_+^2)\right|^2 + 2\left|A(m_+^2,\,m_-^2)\right|\left|A(m_-^2,\,m_+^2)\right| r \cos(\delta + \theta_{(m_+^2,\,m_-^2)} \pm \phi_3)$$

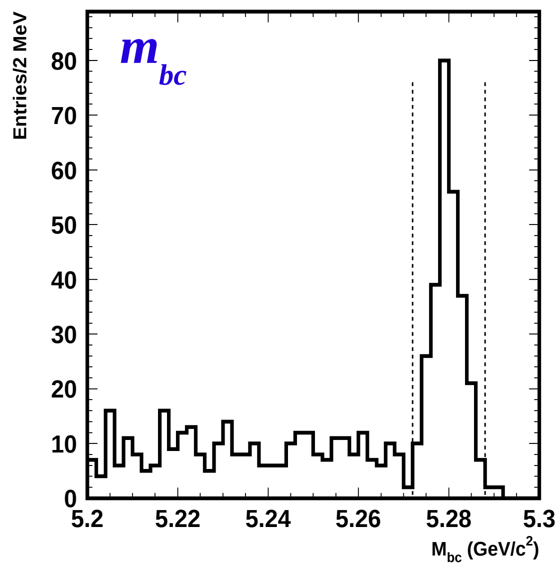
amplitude A determined from $D^0 \to K_s\,\pi^+\pi^-$ Dalitz plot (from continuum)

Measurement of ϕ_3 (hep-ex/0411049)

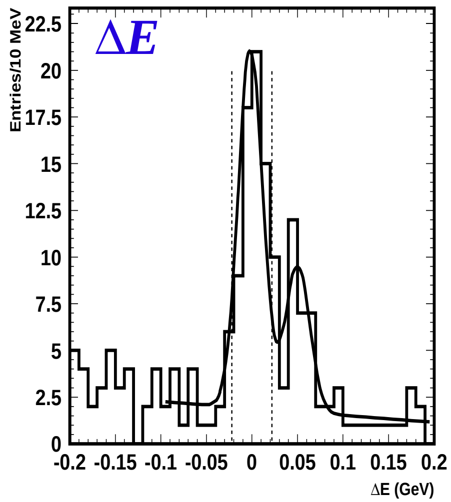
253 fb $^{-1}$

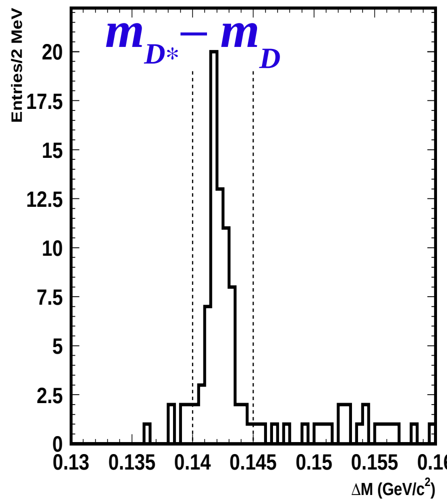
$B^{\pm} \to D^0 K^{\pm}$:
$N = 209 \pm 16$
75% pure

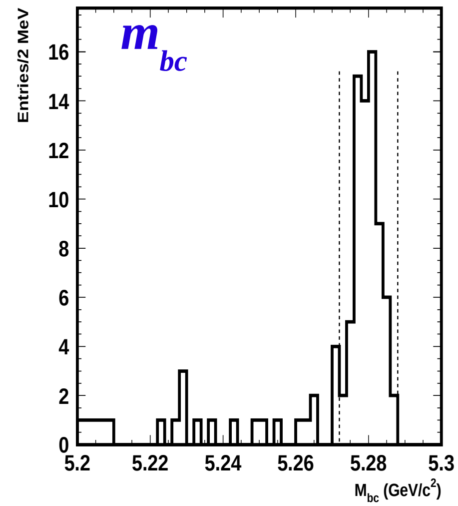




$B^{\pm} \to D^{0*} K^{\pm}$:
$N = 58 \pm 8$
87% pure

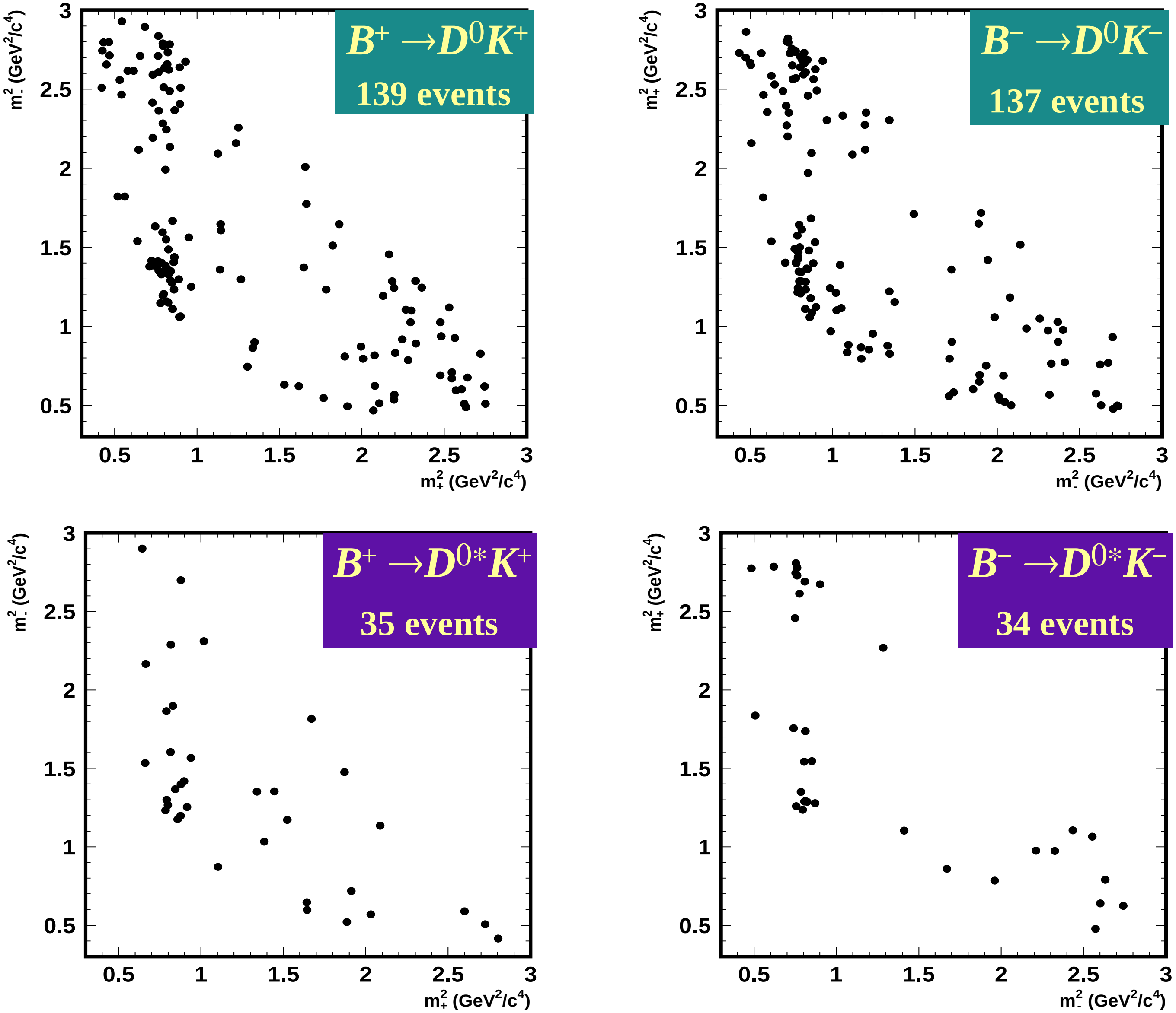






Measurement of ϕ_3 (hep-ex/0411049)

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
$(B^{\pm} \rightarrow D^0 K^{\pm}) + (B^{\pm} \rightarrow D^{0*} K^{\pm})$:

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

$22^{\circ} < \phi_3 < 113^{\circ}$ (95% CL)

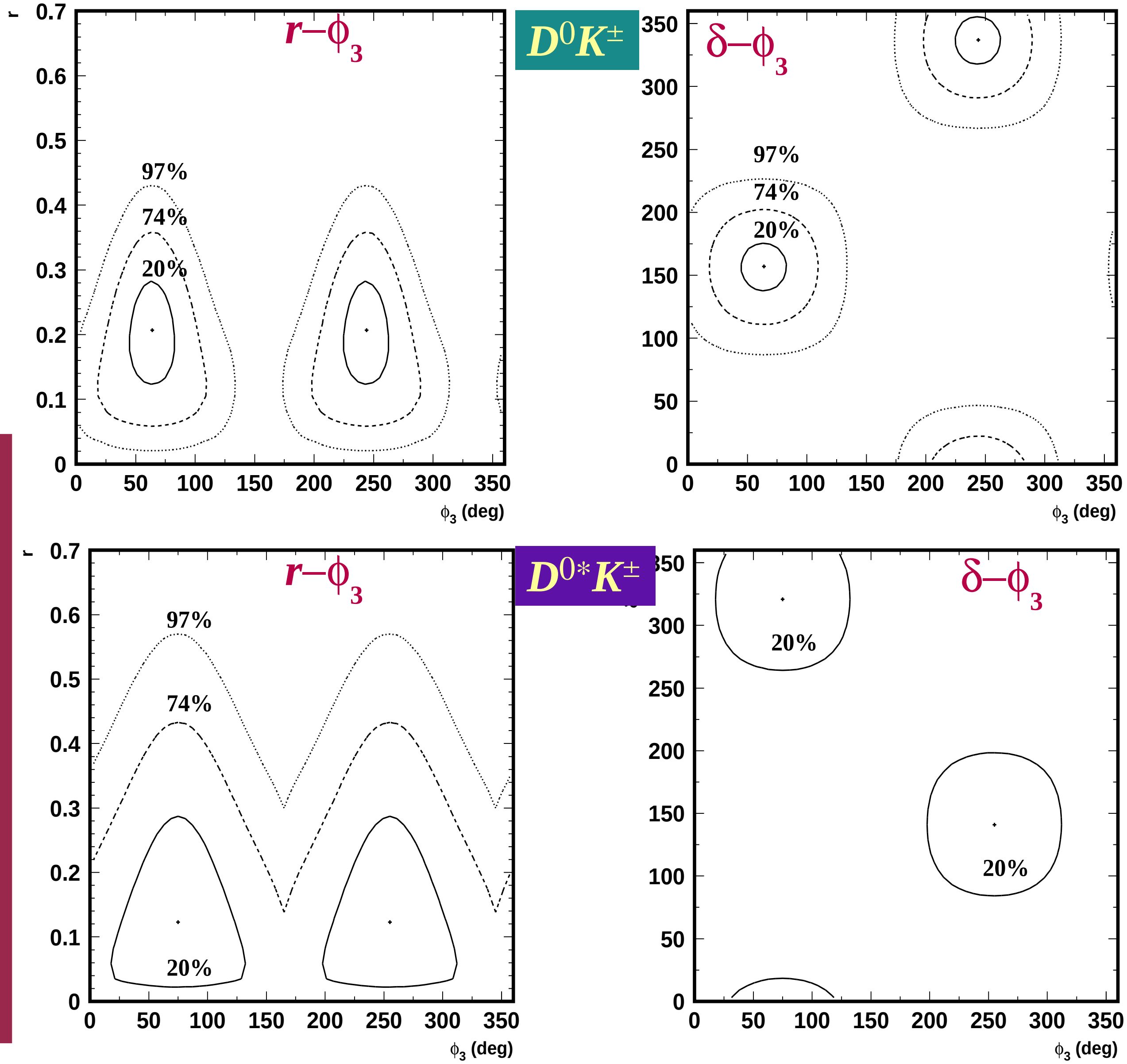
$\delta_D = (157 \pm 19 \pm 11 \pm 21)^{\circ}$

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

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

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

CL of CPV = 98%



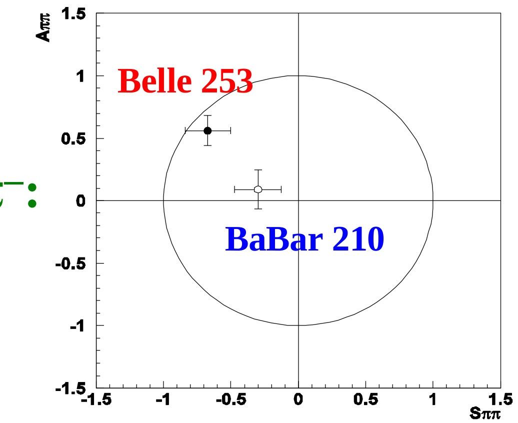
Summary I

357 fb^{-1} :

$\sin(2\phi_1)$: $0.652 \pm 0.039 \pm 0.020 \Rightarrow \phi_1 = (20.3\,^{+1.7}_{-1.6})^o$

b→*qqs* penguin: consistent with SM, largest difference is 2σ (before: 2.3σ for avg.)

253 fb^{-1} :



$\sin(2\phi_2)$: we have observed large *CP* violation in $B \to \pi^+\pi^-$:

$A_{\pi\pi} = +0.56 \pm 0.12$ (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)

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

isospin analysis of $B \to \pi\pi$: $0^o < \phi_2 < 19^o$, $71^o < \phi_2 < 180^o$ (95% CL)

isospin analysis of $B \to \rho\rho$: $59^o < \phi_2 < 115^o$ (90% 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%

Summary II

CKM fitter Belle + BaBar:

- $\phi_1 = (22 \pm 1.2)^o$
- $\phi_2 = (99 +13 -8)^o$
- $\phi_3 = (63 +15 \ -12)^o$

Does the triangle close?

$$\phi_1 + \phi_2 + \phi_3 - 180^o$$
$$= (4 +20 -15)^o$$

Yes! ...and...

outstanding agreement with other measurements (ε, V_{ub}, B^0-B^0 mixing)