Mar.7, 2005

Recent results on CP violation from Belle

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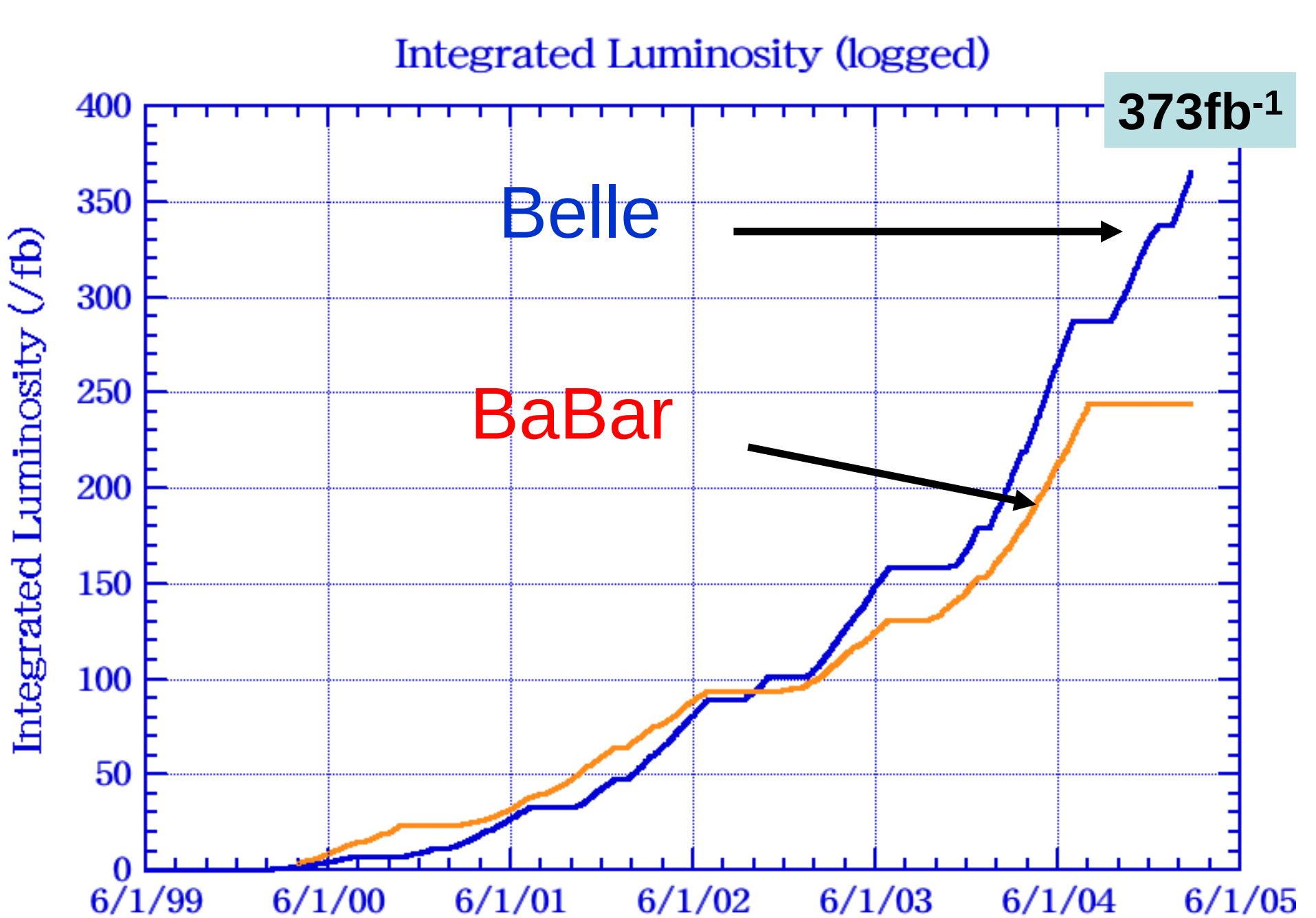
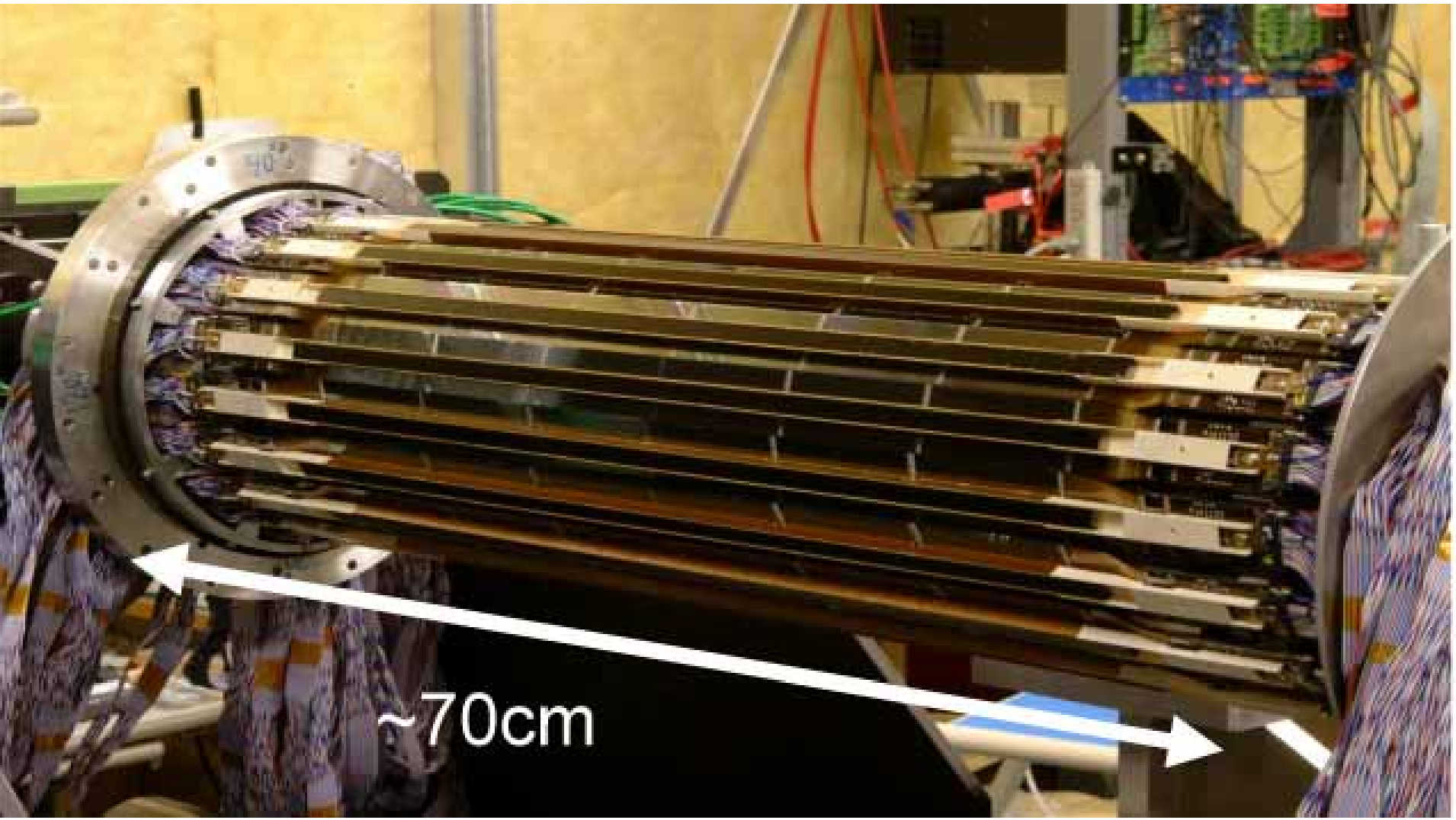
University of Tokyo


Integrated Luminosity (logged)
373fb-1
Belle
BaBar
Integrated Luminosity (/fb)
400
350
300
250
200
150
100
50
0
6/1/99
6/1/00
6/1/01
6/1/02
6/1/03
6/1/04
6/1/05

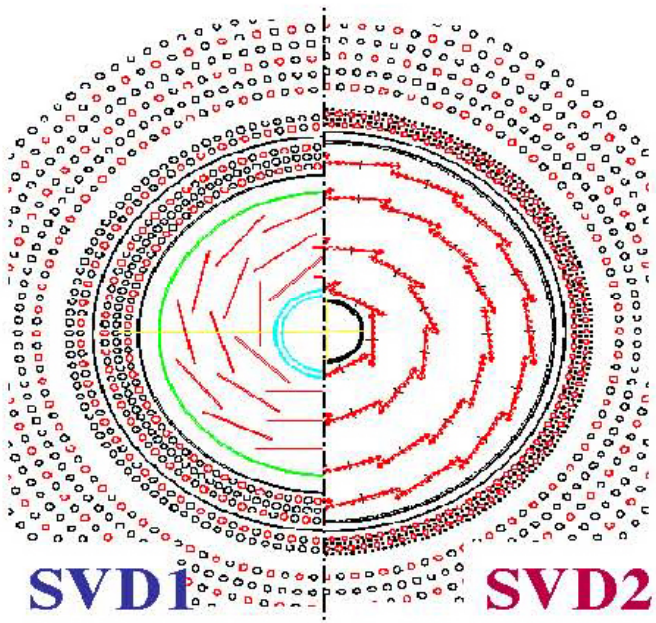
SVD2 installed Summer 2003



The outermost (4th) layer was built with this grant.

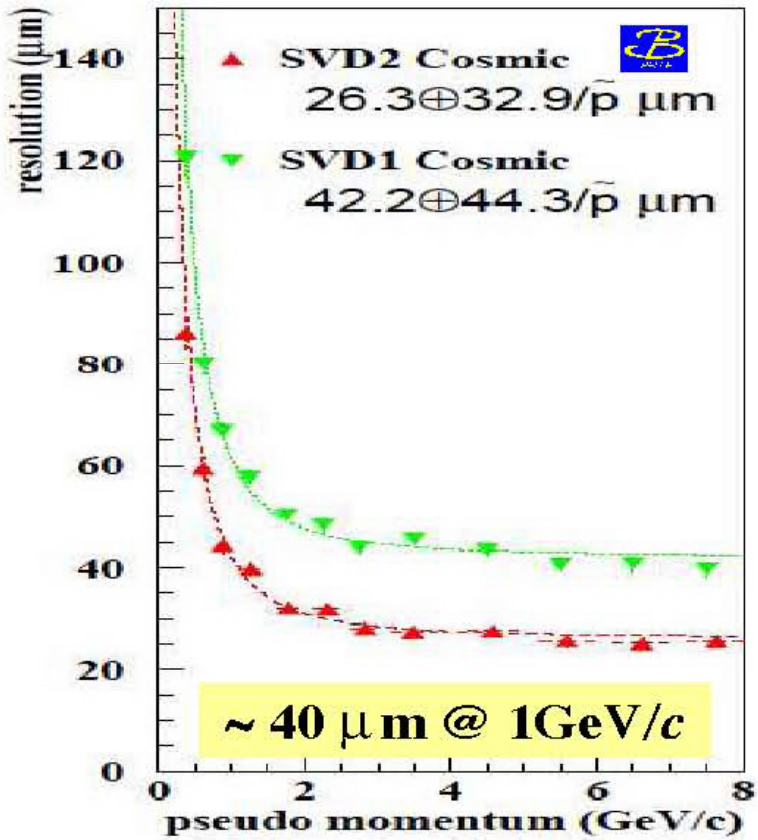
New data set since last result (140 + 113 fb^{-1})

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



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

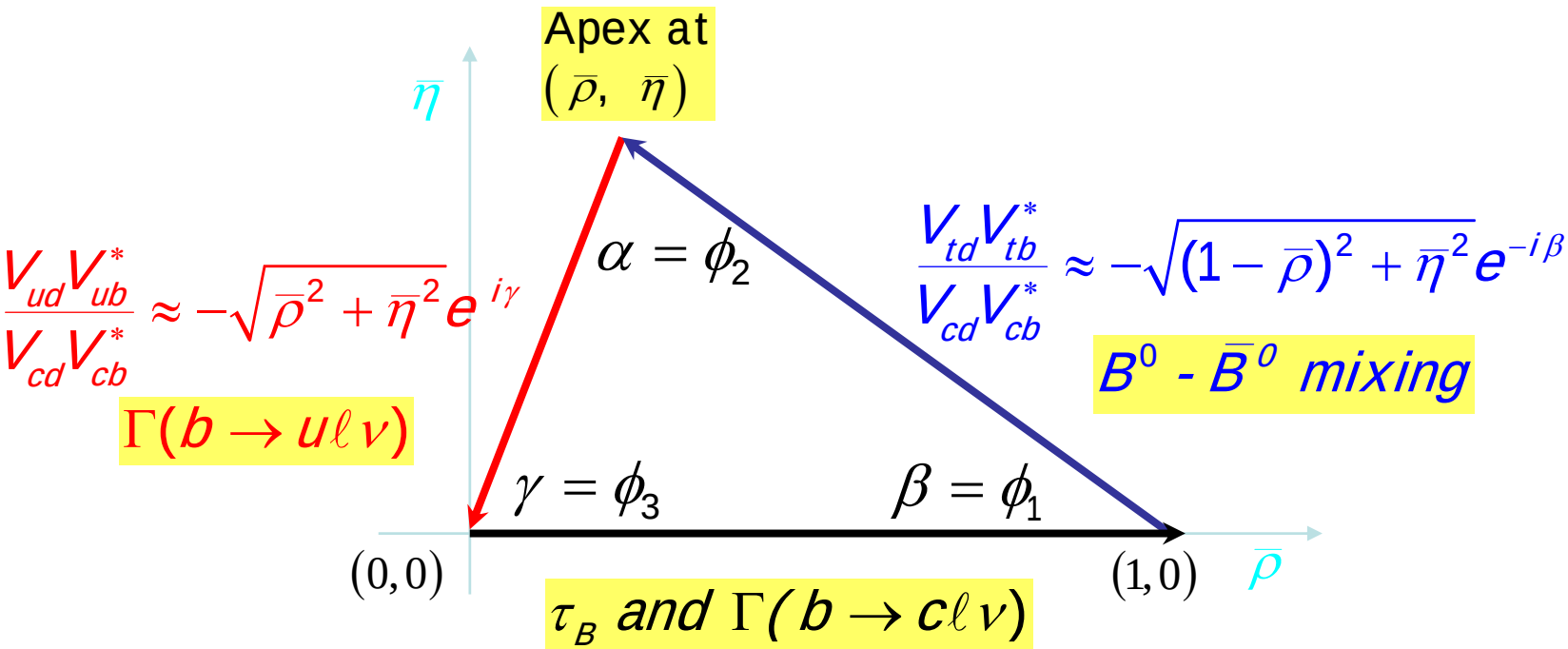
impact parameter resolution (z):



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

Initial goals for B Factories

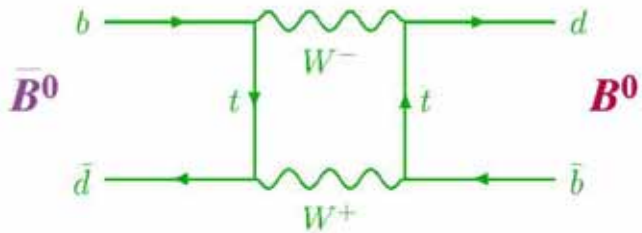
Exploring CKM picture or alternative origins for *CP* violation for quark sector



$$\beta = -\arg V_{td};\ \gamma = \arg V_{ub}^*;\ \ \alpha = \pi - \gamma - \beta$$

Introduction

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

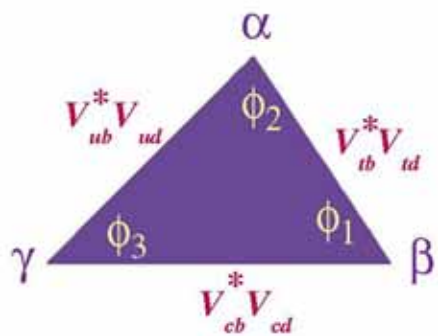


$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}} \approx \sqrt{\frac{M_{12}^*}{M_{12}}} = e^{i2\phi_1} \qquad \text{(phase of } V_{td}^* V_{tb}\text{)}$$

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

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

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



Measurement of $\sin(2\phi_1)$

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

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

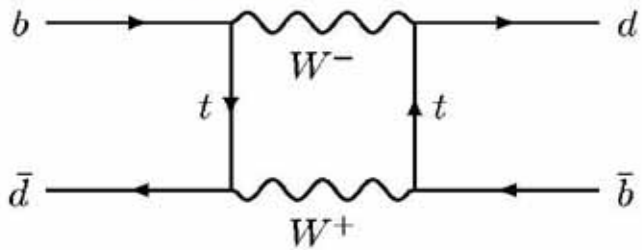
$$= -\frac{-V_{cb}V_{cd}^*/(V_{td}^*V_{tb})}{-V_{cb}^*V_{cd}/(V_{td}V_{tb}^*)}$$

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

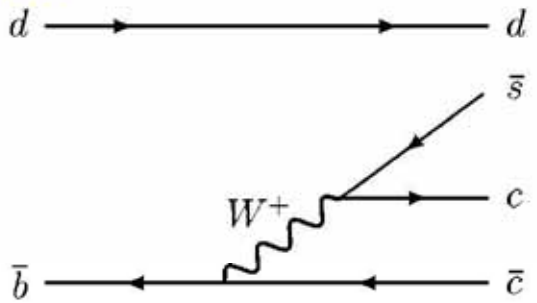
$$= -e^{-2i\phi_1}$$

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

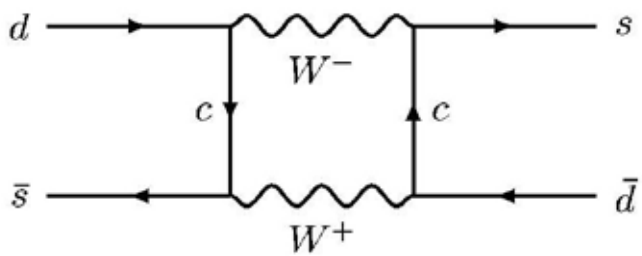
$\bar{B}^0$-B^0 oscillation:



Tree:

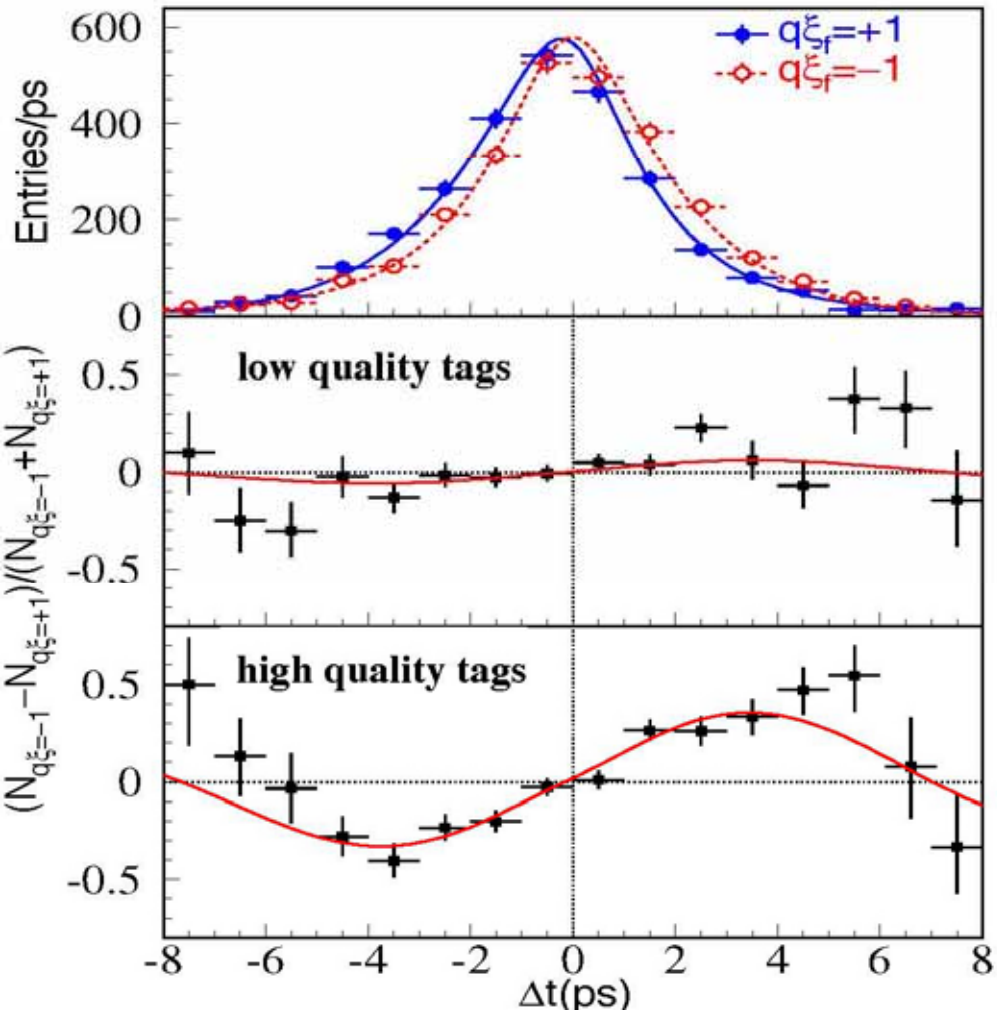


$\bar{K}^0$-K^0 oscillation:



Status of ϕ_1 (=β)

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



140 fb^{-1}:

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

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

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

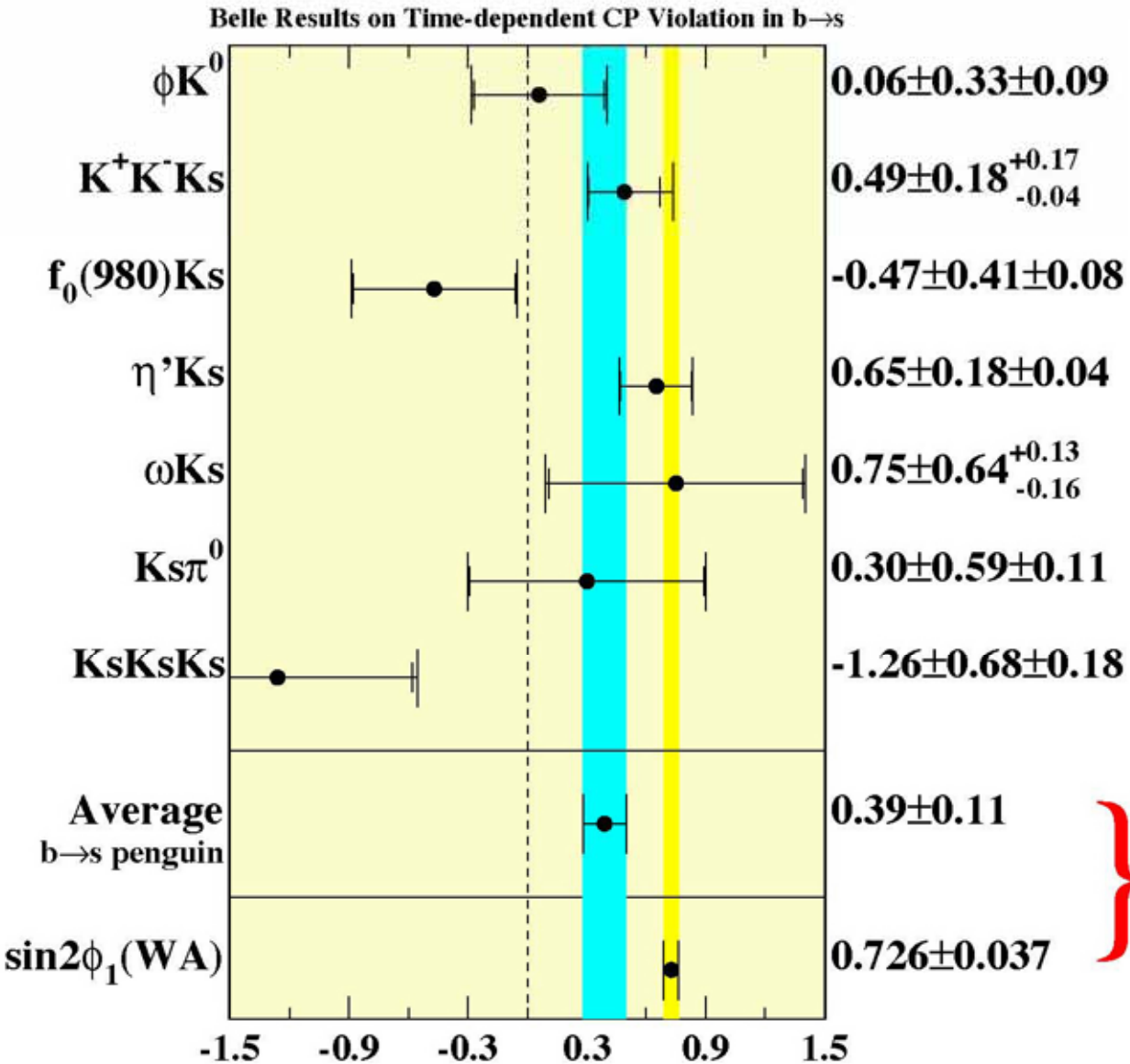
close to BaBar 210 fb^{-1}:

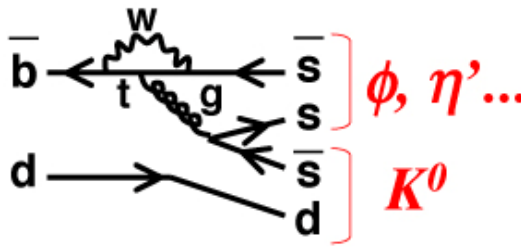
$\sin(2\phi_1) = 0.722 \pm 0.040 \pm 0.023$

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

$\phi_1 = (23.5 \pm 1.6)^\circ \quad (\text{Belle+Babar})$

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





2.9σ difference ⇒ more statistics needed

Compelling evidence for
direct CP violation in B^0 to $\pi^+\pi^-$ decay
and
model-independent constraints on $\phi_2(\alpha)$
based on 275M BBbar pairs

Measurement of $\sin(2\phi_2)$

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

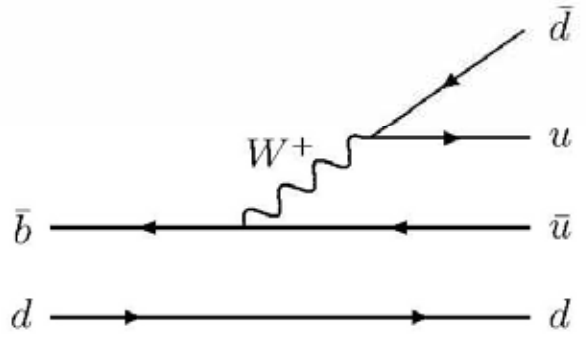
$$= \frac{-V_{tb}^*V_{td}/(V_{ub}^*V_{ud})}{-V_{tb}V_{td}^*/(V_{ub}V_{ud}^*)}$$

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

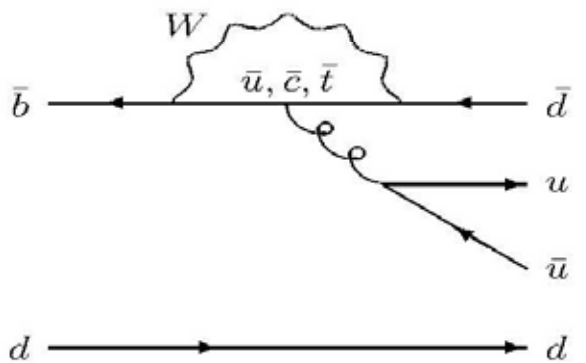
$$= e^{2i\phi_2}$$

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

Tree:



Penguin:



...if no penguin. But there is a penguin contribution, and it "breaks" these simple equalities

Previously……

Belle 152 M $B\bar{B}$

with 372±32 $B^0 \to \pi^+\pi^-$ events

$$S_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07$$
$$A_{\pi\pi} = +0.58 \pm 0.15 \pm 0.07$$

PRL 93, 021601 (2004)

BABAR 227M $B\bar{B}$

with 467±33 $B^0 \to \pi^+\pi^-$ events

$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$A_{\pi\pi} = +0.09 \pm 0.15 \pm 0.04$$

hep-ex/0501071

CPV with 5.2σ,

3.2σ evidence for DCPV

3.2σ difference

Event Selection

- $B^0 \to \pi^+\pi^-$ selection

Pion Identification using aerogel and dE/dx

$$\varepsilon(\pi) \cong 90\% \quad p(K \to \pi) \cong 11\%$$

Kinematical Selection

$$5.271 < M_{bc} < 5.287 GeV/c^2$$

$$|\Delta E| < 0.064 GeV$$

corresponding to ±3σ

$$\Delta E = E_B^{CMS} - E_{beam}^{CMS}$$

$$M_{bc} = \sqrt{(E_{beam}^{CMS})^2 - (p_B^{CMS})^2}$$

Flavor Tagging

q: flavor charge

q=+1 tagged as a B^0,
q=−1 tagged as a $\overline{B}^0$

r: dilution factor
$0<r\leq 1$

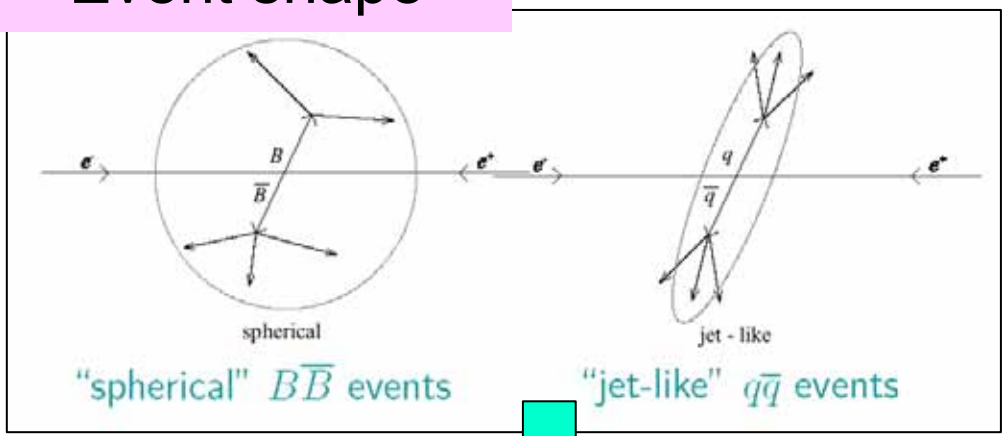
r=0 no flavor discrimination,

r=1 unambiguous flavor assignment

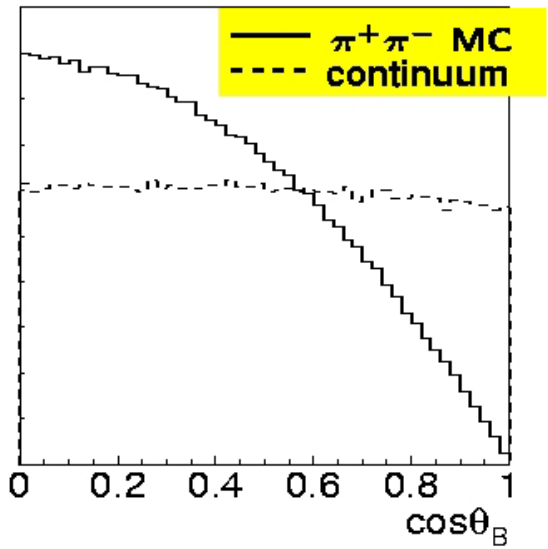
Event Selection (continuum suppression)

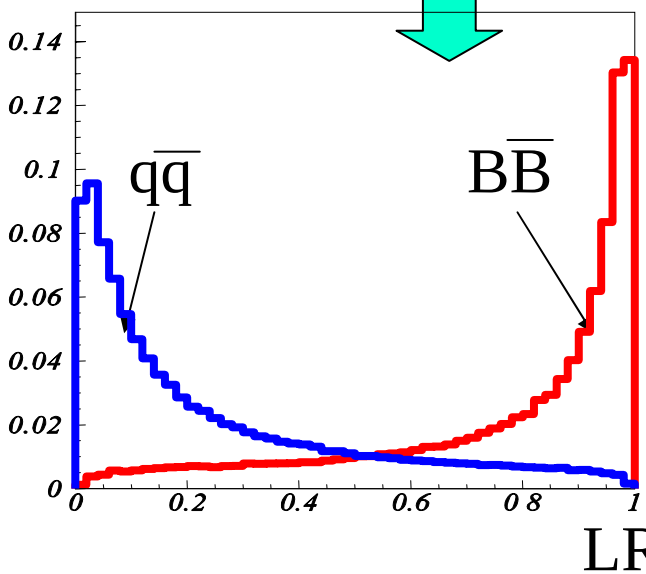
$$e^+e^- \to q\bar{q}, (q = u, d, s, c)$$

Event shape



B flight direction



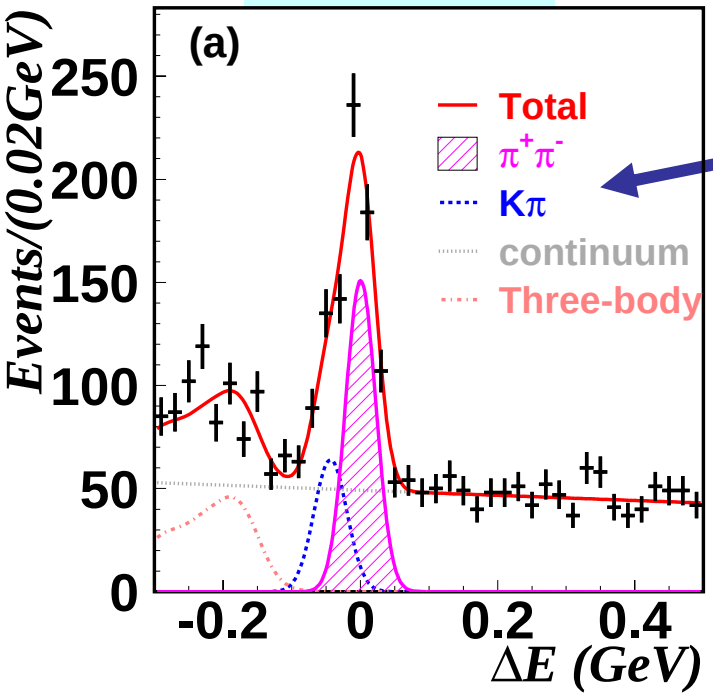


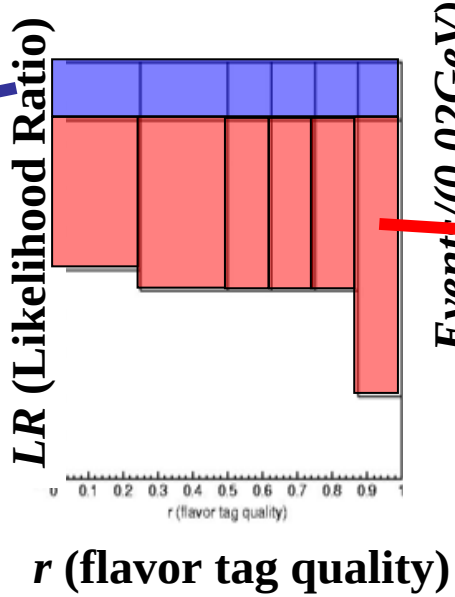
$$LR = \frac{\mathcal{L}_{B\bar{B}}}{\mathcal{L}_{B\bar{B}} + \mathcal{L}_{q\bar{q}}}$$

(Likelihood Ratio)

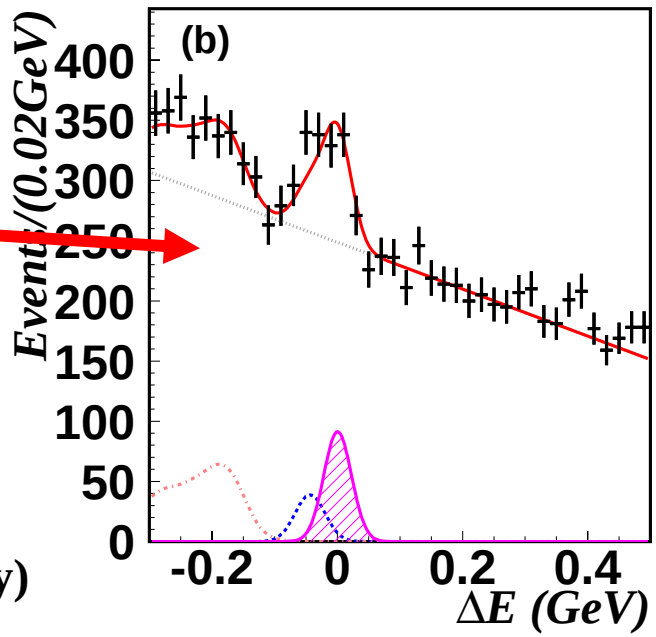
$B^0 \to \pi^+\pi^-$ signals from 275M BBbar events

(LR>0.86)



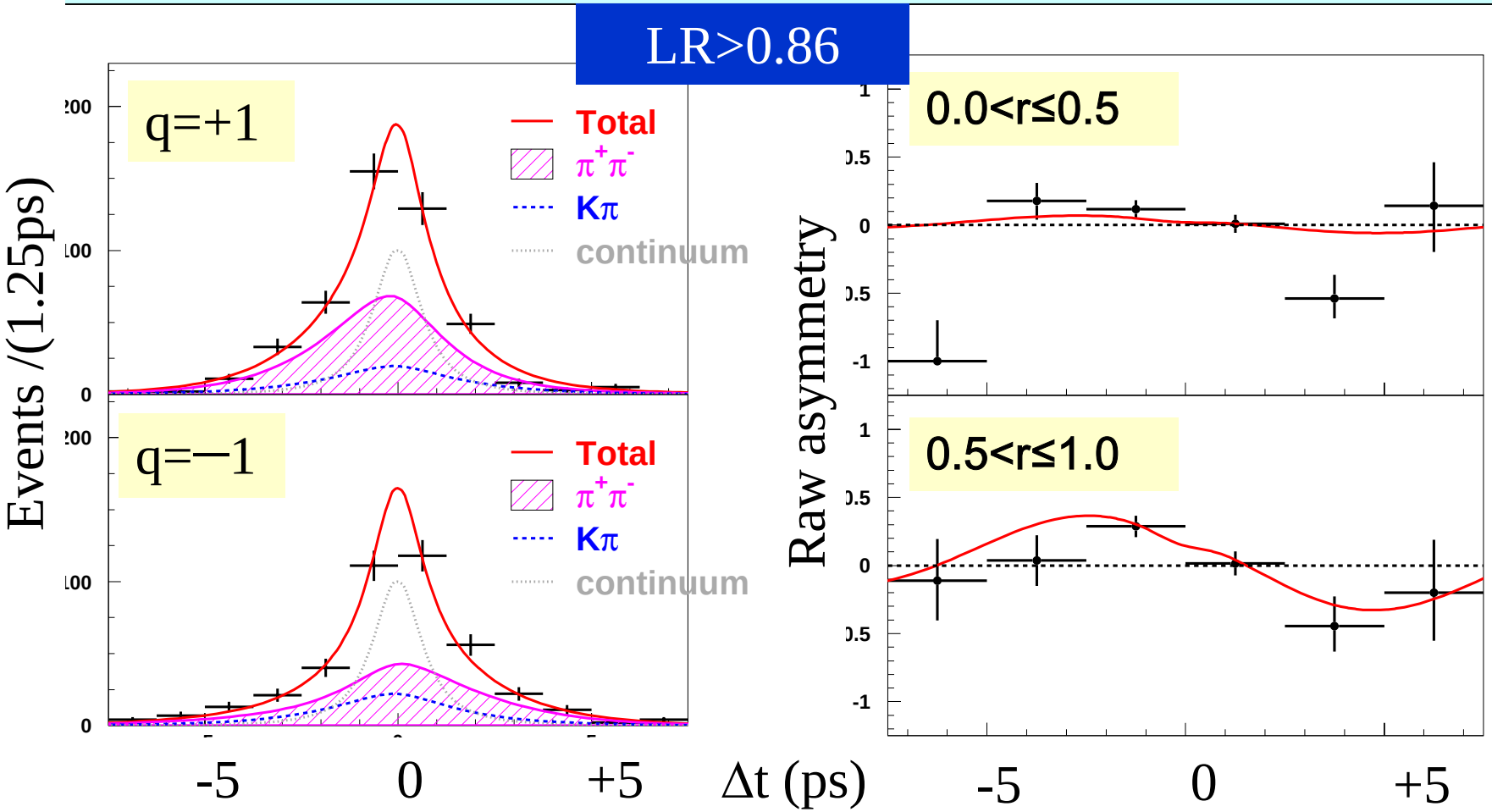


(LR<0.86)



2,820 candidates containing (666 ± 43) $\pi^+\pi^-$ signal events

Unbinned CP fit results

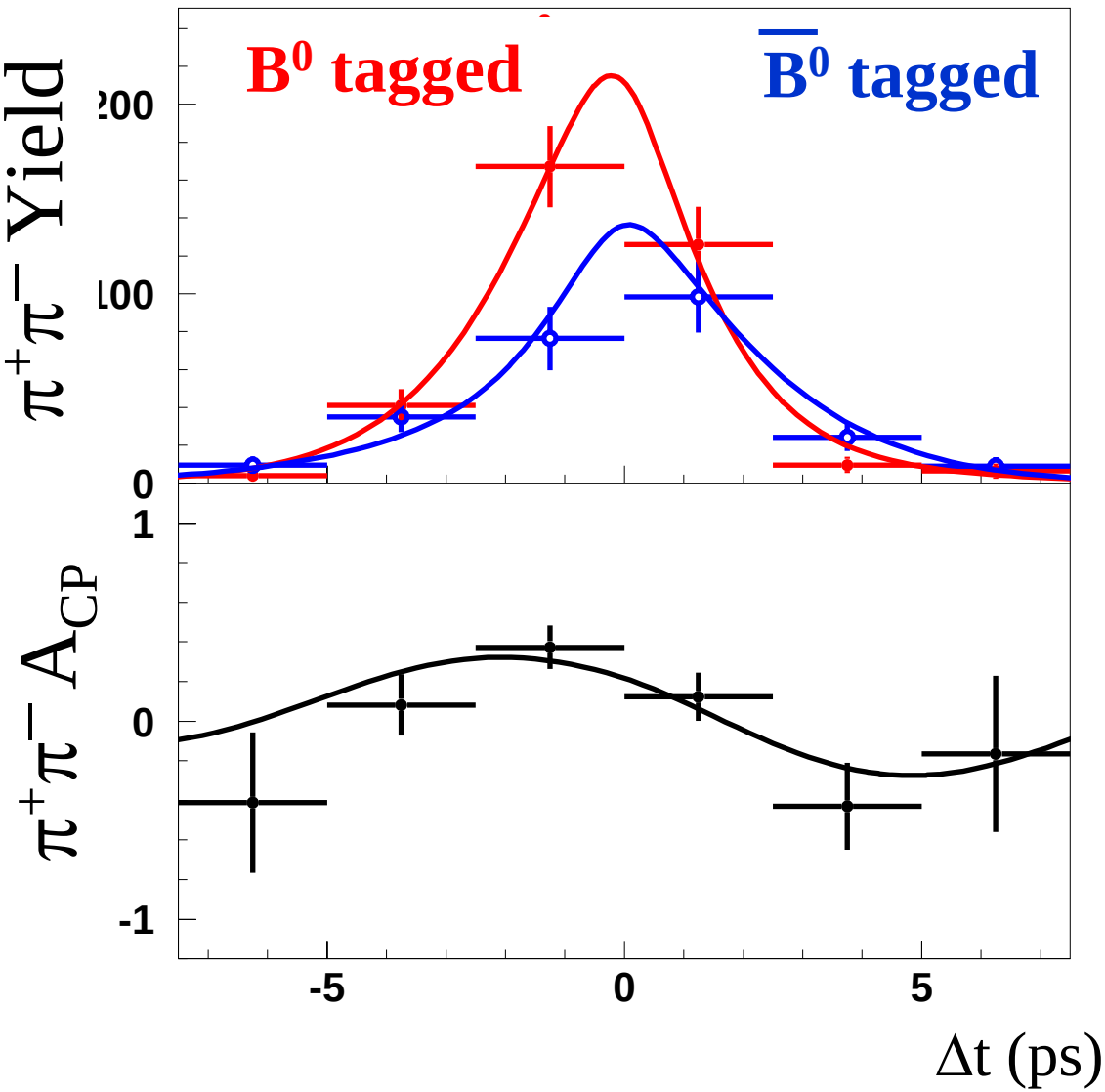


$$A_{\pi\pi} = +0.56 \pm 0.12 \pm 0.06$$

$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$$

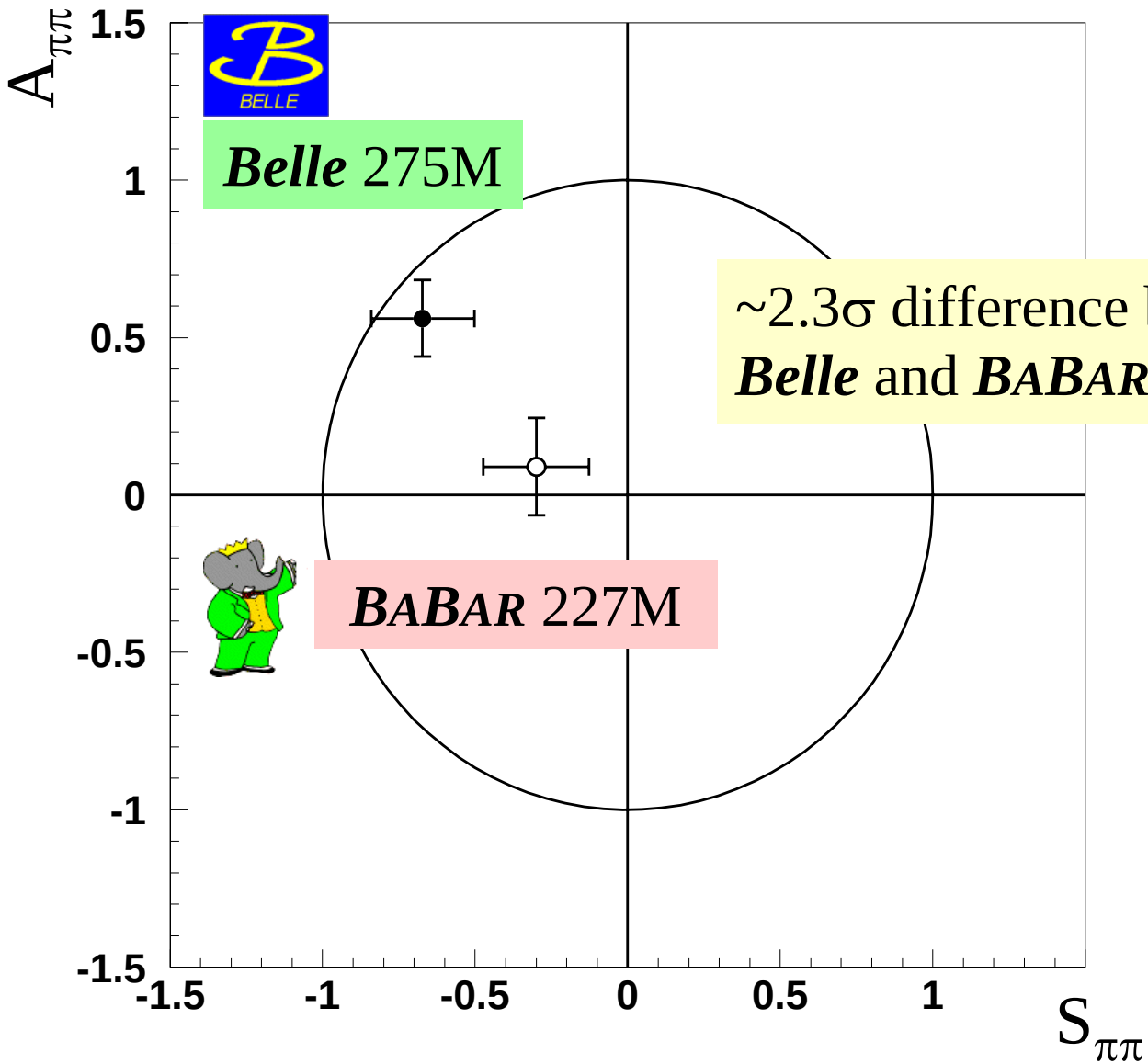
1st error statistical,
2nd systematic

Background subtracted fit projection for all events

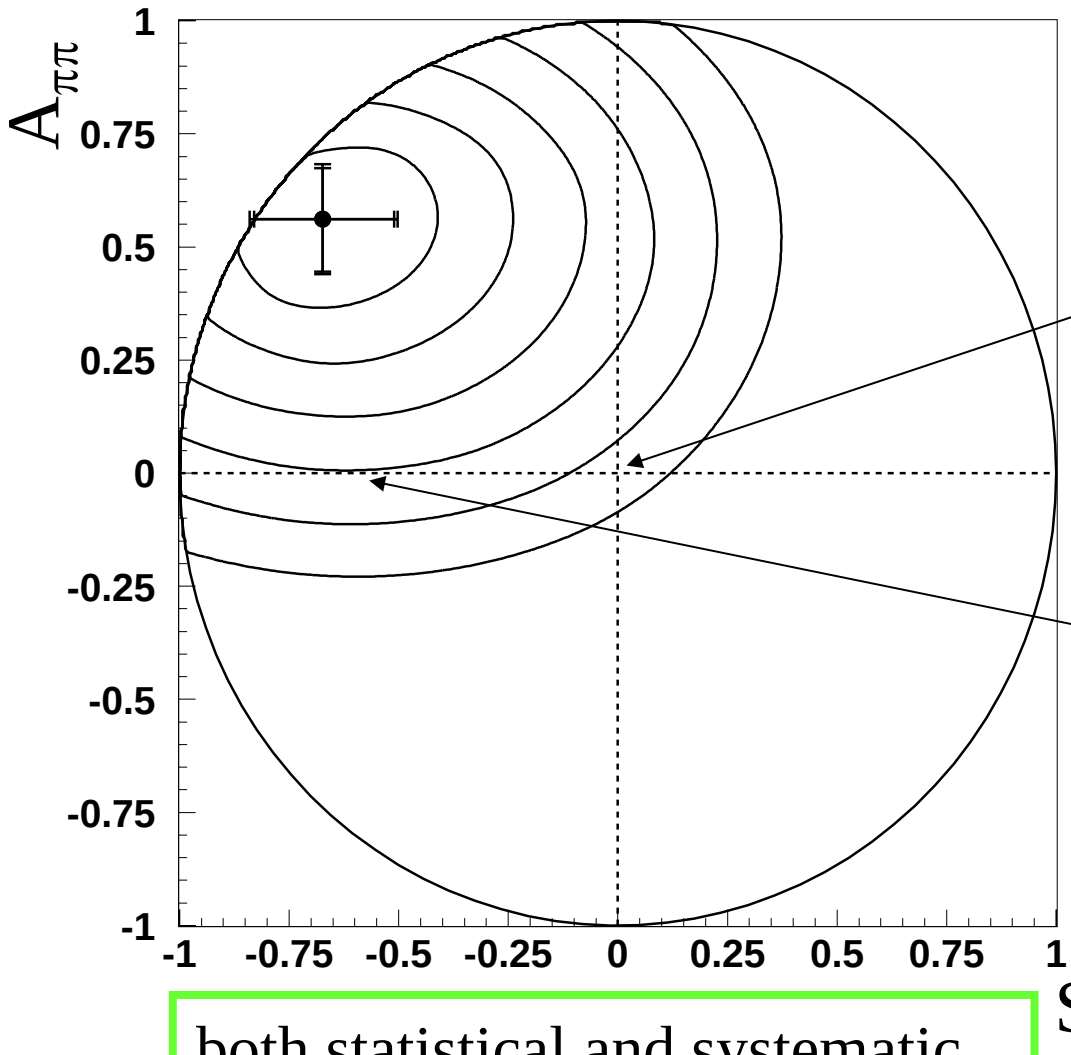


ΔE-Mbc 2D fits to individual time intervals

New experimental situation



Significance calculation with Feldman-Cousins method



Large CP Violation,

(A,S)=(0,0)
1-C.L.=5.62×10^{-8}, 5.4σ

(A,S)=(0,−0.62)
1-C.L.=5.13×10^{-5}, 4.0σ

Large Direct CP violation, confirmation of the previous Belle results

both statistical and systematic errors are taken into account.

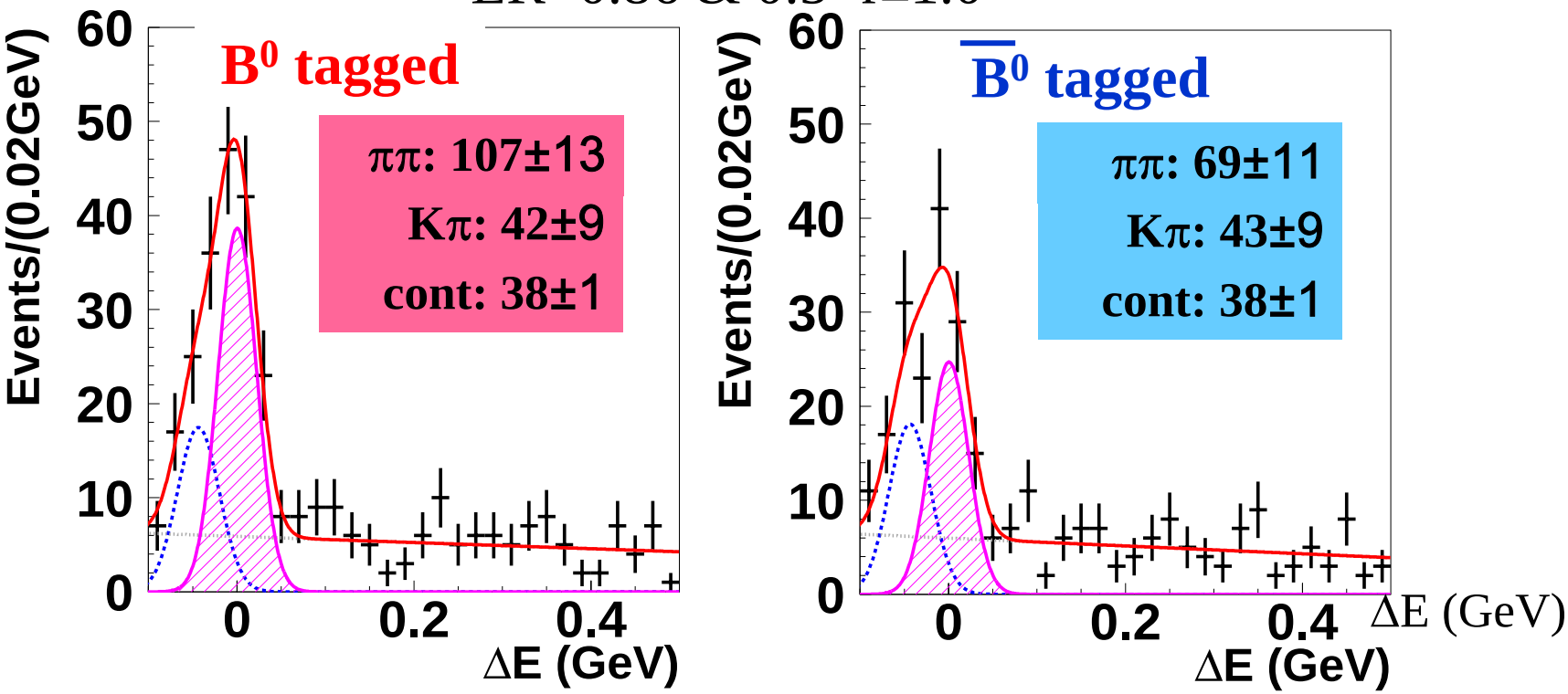
C.L. = Confidence Level

Consistency checks with Time-integrated fits

$A_{\pi\pi} = +0.52 \pm 0.14$

consistent with time-dependent fit

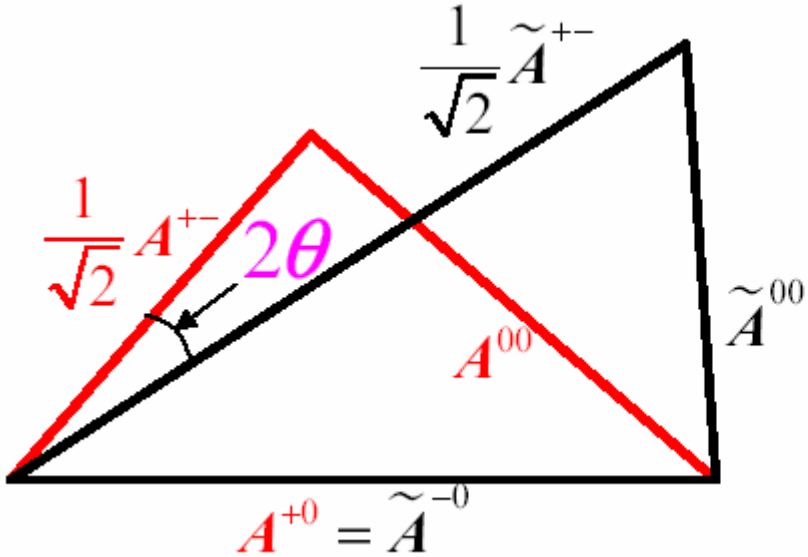
LR>0.86 & 0.5<r≤1.0



Direct CP Violation is evident!

Interpretation: ϕ_2 constraint using isospin

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



	Amplitude for
$A^{+-}(\bar{A}^{+-})$	$B^0(\bar{B}^0) \to \pi^+\pi^-$
$A^{00}(\bar{A}^{00})$	$B^0(\bar{B}^0) \to \pi^0\pi^0$
$A^{+0}(\bar{A}^{-0})$	$B^+(B^-) \to \pi^+\pi^0(\pi^-\pi^0)$

$$\tilde{A}^{ij} = e^{2\phi_3}\bar{A}^{ij}$$

$$S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}^2}\,\sin(2\phi_2 + 2\theta)$$

The cleanest method to extract ϕ_2

We use the HFAG summer 2004 values for the branching ratios of $B^0 \to \pi^+\pi^-$, $\pi^0\pi^0$, $B^+ \to \pi^+\pi^0$ and direct CP asymmetry of $B^0 \to \pi^0\pi^0$.

We use the statistical treatment of
J. Charles *et al.*, hep-ph/0406184

$B^0 \to \pi^0\pi^0$ branching ratio and asymmetry

Belle measurement with 275M $B\bar{B}$ pairs

$$Br(\pi^0\pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$$
$$A_{CP}(\pi^0\pi^0) = +0.44^{+0.53}_{-0.52} \pm 0.17$$

hep-ex/0408101
submitted to PRL

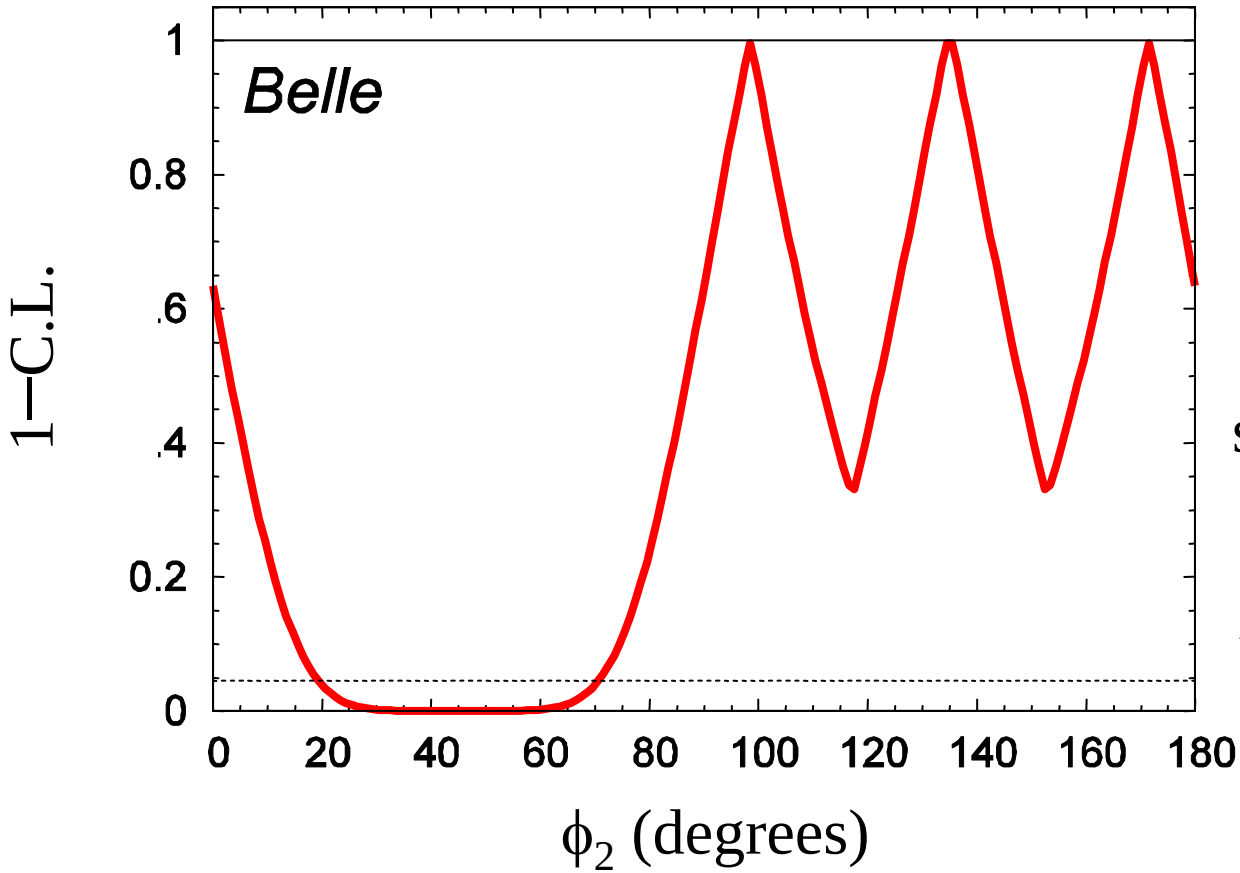
BABAR measurement with 227M $B\bar{B}$ pairs

$$Br(\pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$
$$A_{CP}(\pi^0\pi^0) = +0.12 \pm 0.56 \pm 0.06$$

hep-ex/0412037
submitted to PRL

First $A_{CP}(B^0 \to \pi^0\pi^0)$ measurements in summer 2004.

Interpretation : ϕ_2 constraint with isospin



using HFAG summer 2004

J. Charles *et al.*, hep-ph/0406184

95.4% confidence interval

$0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$

Summary of new Belle $B^0 \to \pi^+\pi^-$ CP results

- The fit yields

$$A_{\pi\pi} = +0.56 \pm 0.12 \pm 0.06$$
$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$$

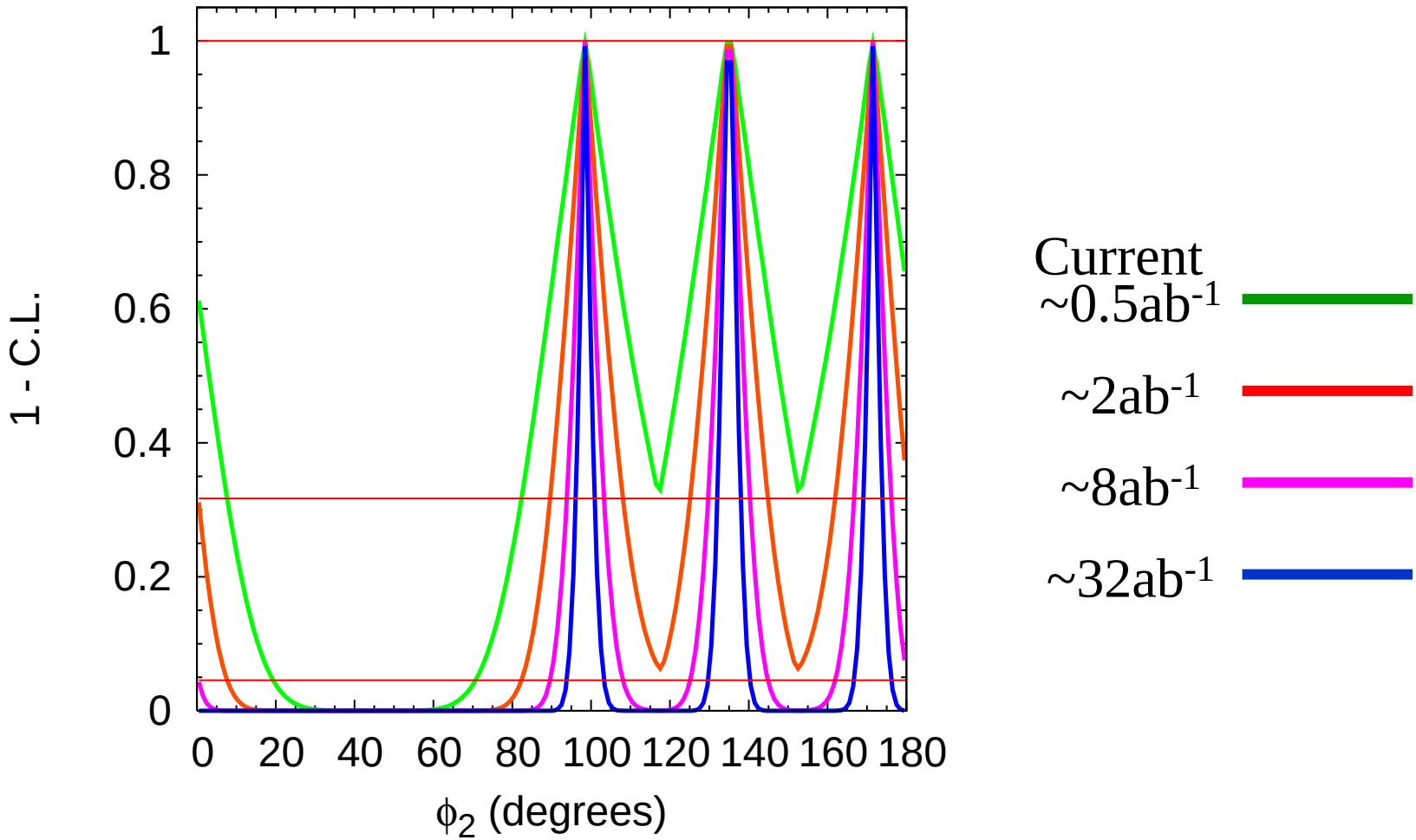
1st error statistical,
2nd systematic

- Large direct CP violation with 4.0σ significance is observed
- The results confirm the previous Belle results.
- Isospin analysis gives at 95.4% C.L.

$$0^\circ < \phi_2 < 19^\circ \quad \& \quad 71^\circ < \phi_2 < 180^\circ$$

Outlook

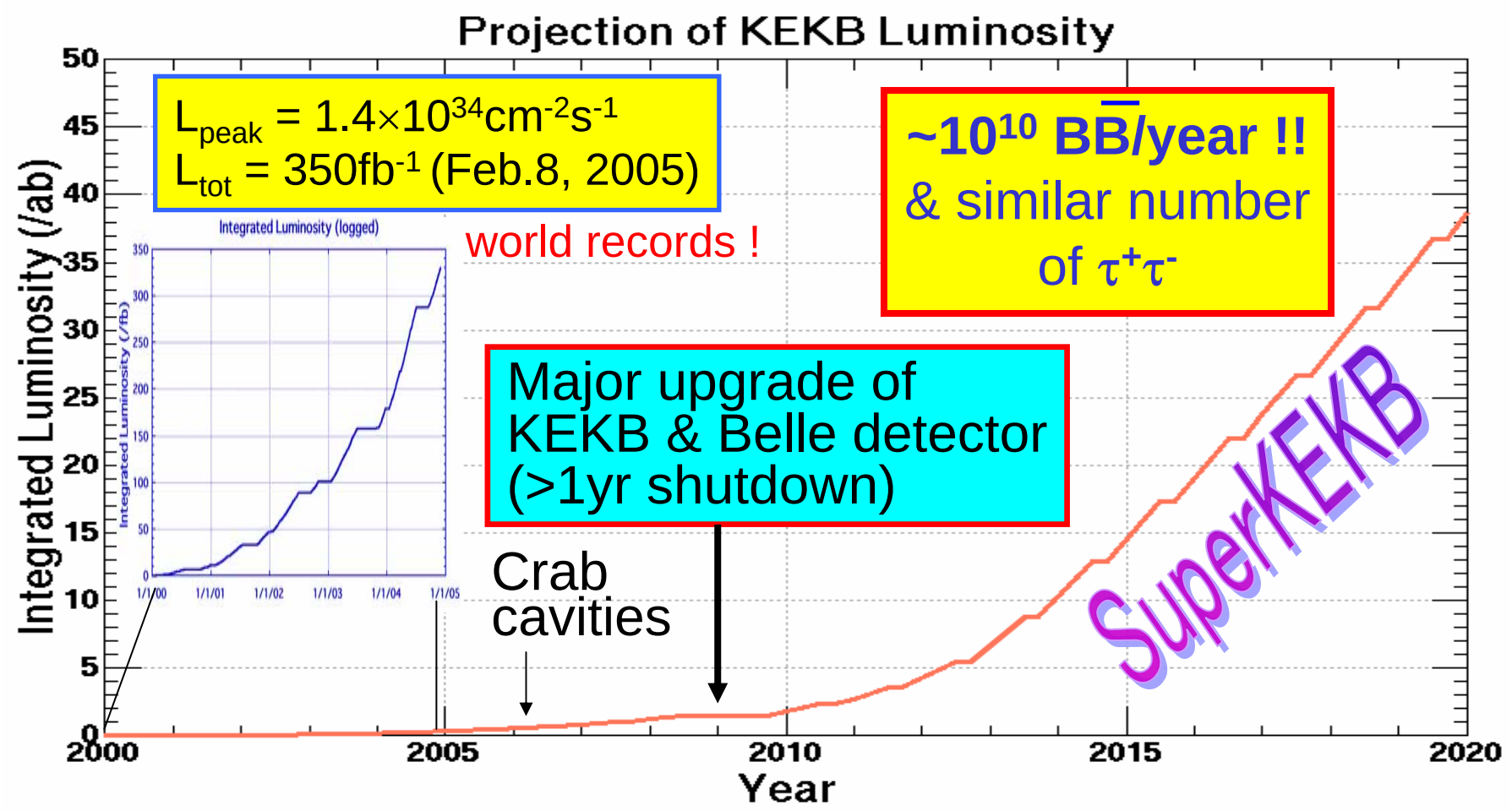
assuming the current measured values



Takes Super-B factories to really pin down the ϕ_2 value.

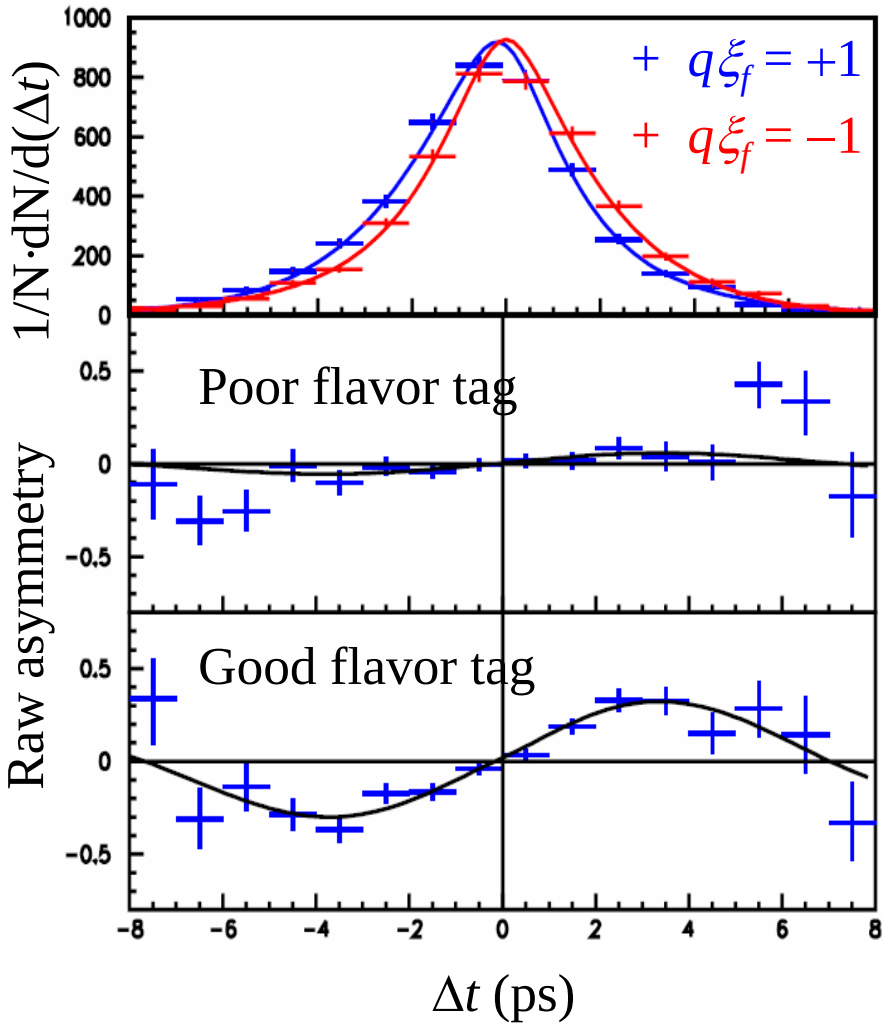
End

Future prospect



L_{peak} (cm^{-2}s^{-1})	1.4x10^{34}	5x10^{34}	5x10^{35}
L_{int}	330 fb^{-1}	~1 ab^{-1}	~10 ab^{-1}

sin2ϕ_1 result : 274M $B\bar{B}$ Pairs



J/ψ K⁰ only ***preliminary***

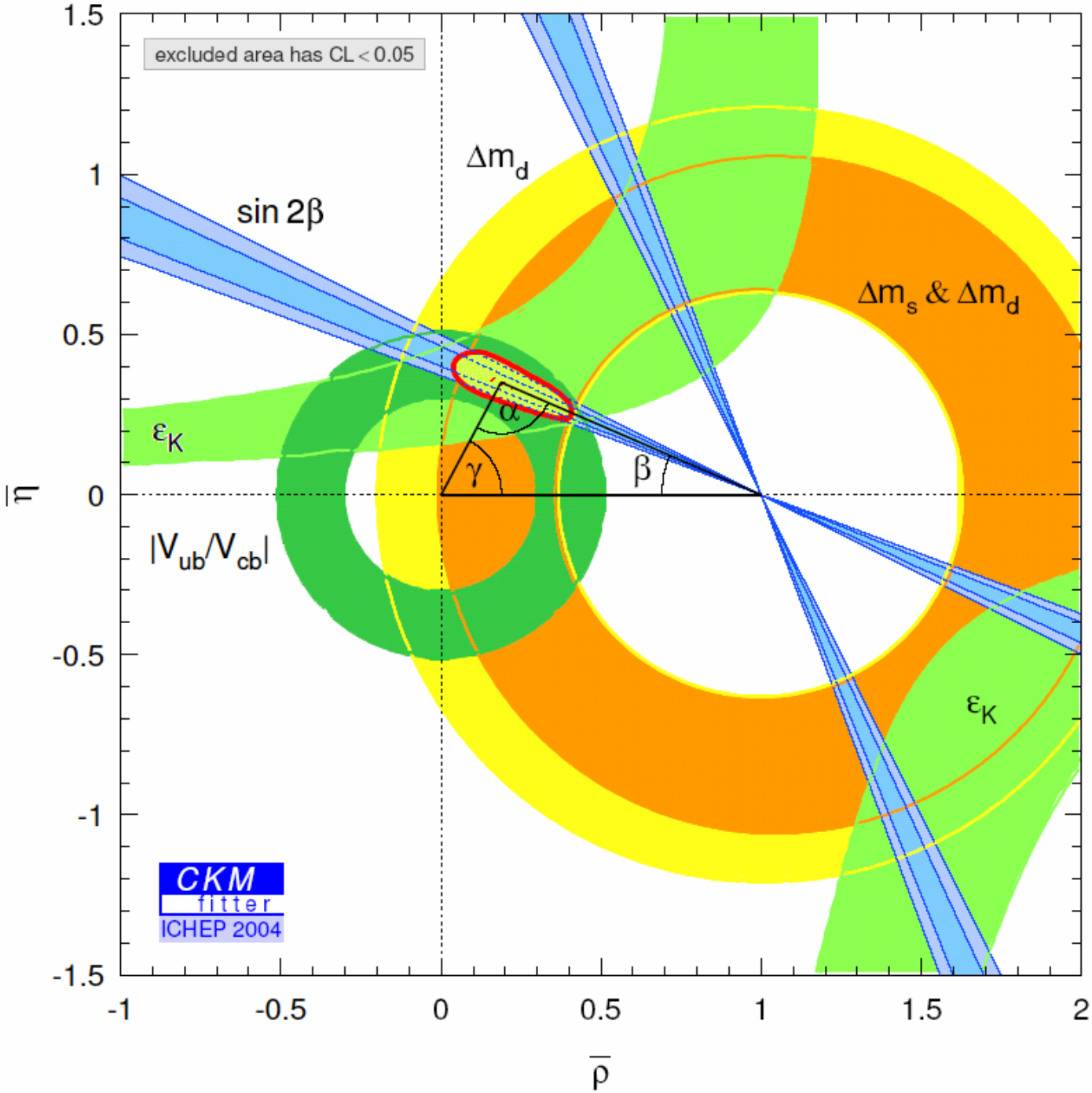
sin2ϕ_1 = 0.666 ± 0.046
A = 0.023 ± 0.031

Before upgrade (152M $B\bar{B}$)

sin2ϕ_1 = 0.696 ± 0.061
A = 0.011 ± 0.043

After upgrade (122M $B\bar{B}$)

sin2ϕ_1 = 0.629 ± 0.069
A = 0.035 ± 0.044


excluded area has CL < 0.05
Δm_d
sin 2β
Δm_s & Δm_d
ε_K
α
γ
β
|V_ub/V_cb|
ε_K
CKM fitter
ICHEP 2004
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2
η̄
ρ̄