CP Violation at Belle and Beyond

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Introduction

Observation of CPV outside of the kaon sector.

Controversies.

The Future.

KM ansatz: CPV is due to a complex phase in the quark mixing matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The B Physics Program

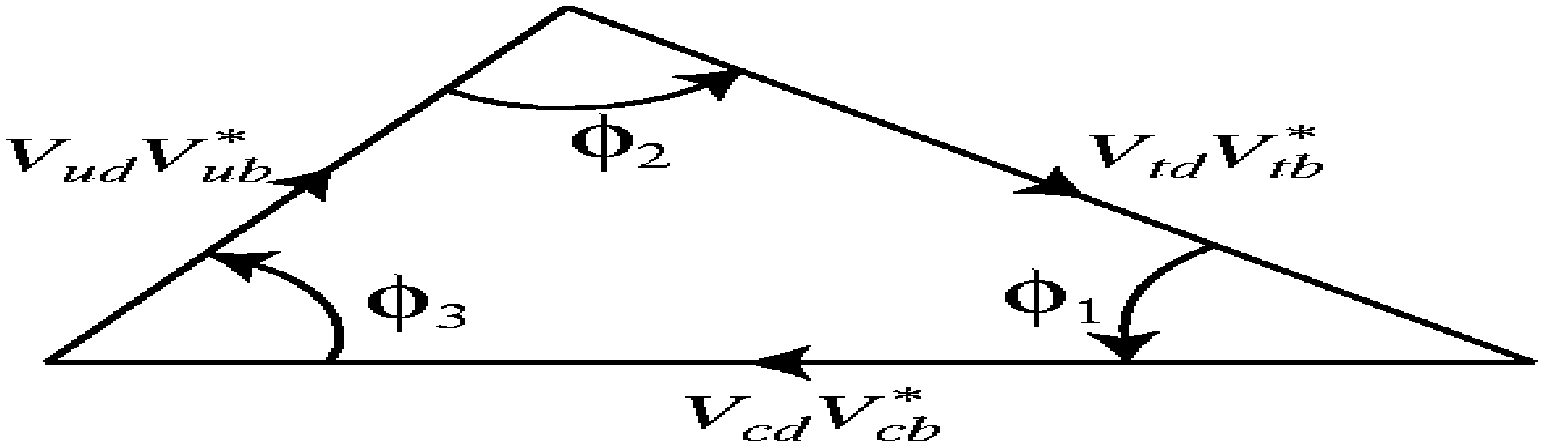
Quark couplings are complex and lead to CP violation. *Is CP violation a result of a single weak phase in the KM matrix ?*

Or is it a signal of new interactions beyond the Standard Model ?

Is there new physics in loop decays ?

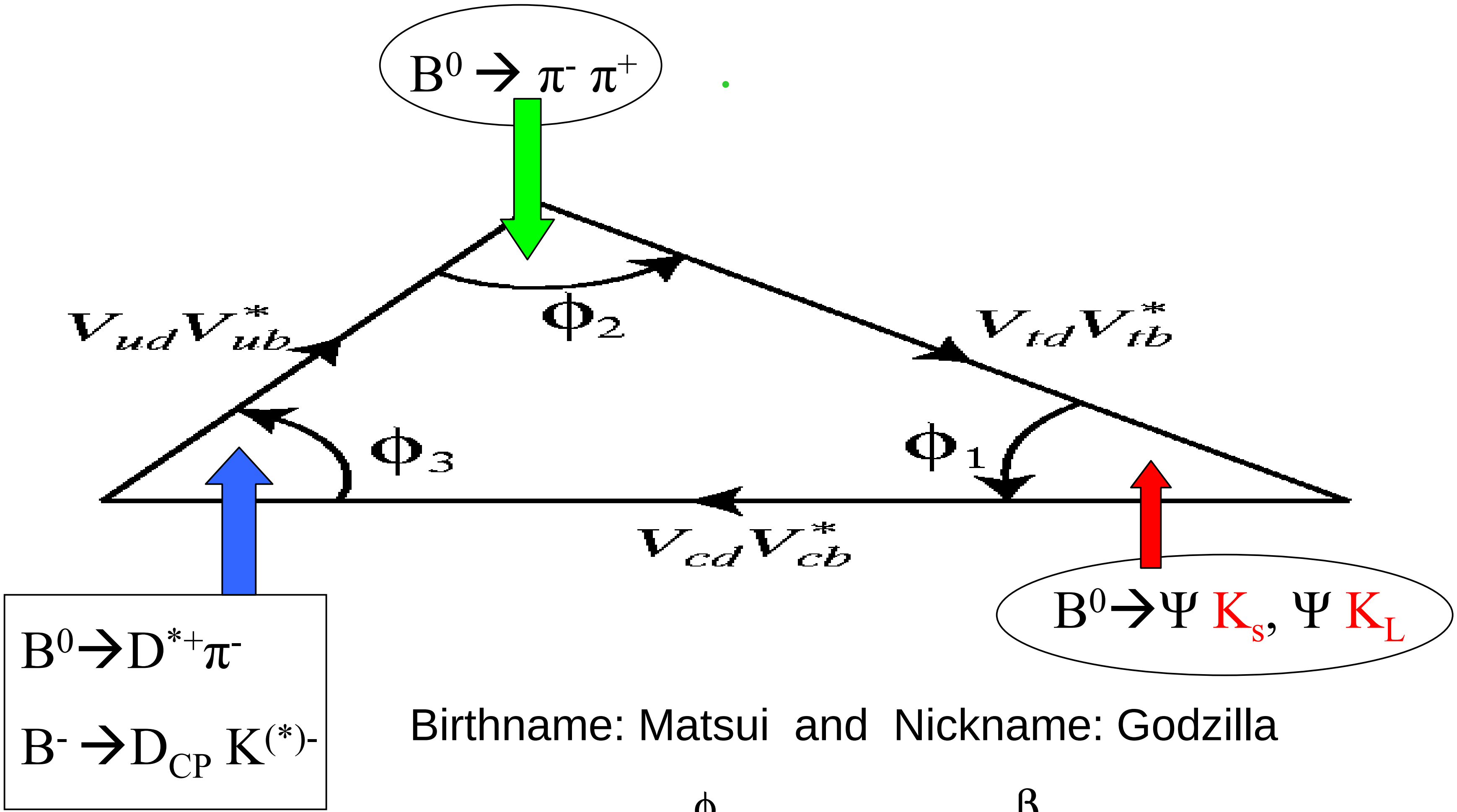
Notational Conventions

Three Angles: $(\varphi_1, \varphi_2, \varphi_3)$ *or* (β, α, γ)



Birthname: Matsui	Nickname: Godzilla
ϕ_1	β
ϕ_2	α
ϕ_3	γ

Three Angles: $(\varphi_1, \varphi_2, \varphi_3)$ or (β, α, γ)

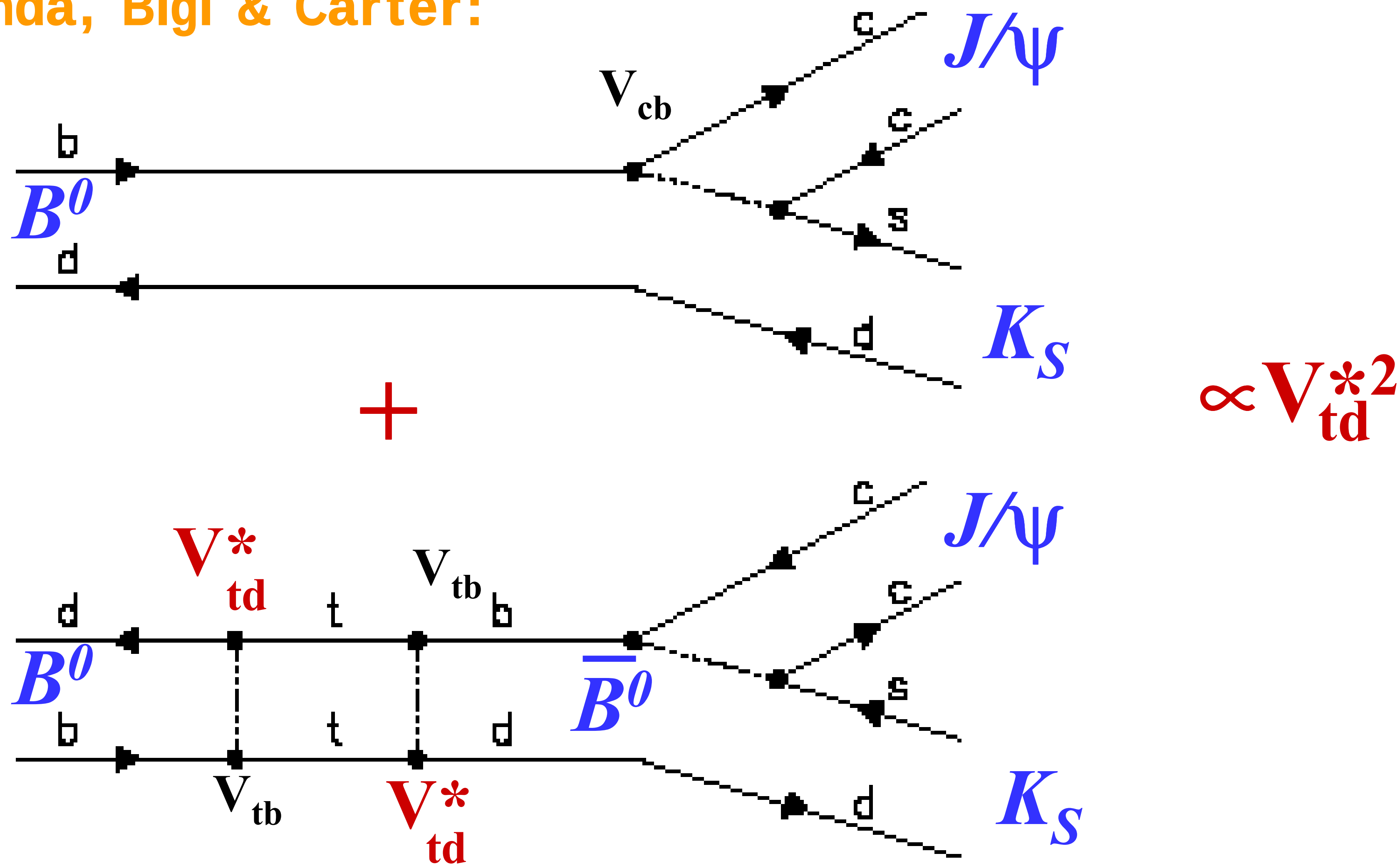


Birthname: Matsui and Nickname: Godzilla

ϕ_1	β
ϕ_2	α
ϕ_3	γ

$\sin 2\phi_1$ from $B \to f_{CP} + B \leftrightarrow \overline{B} \to f_{CP}$ interf.

Sanda, Bigi & Carter:

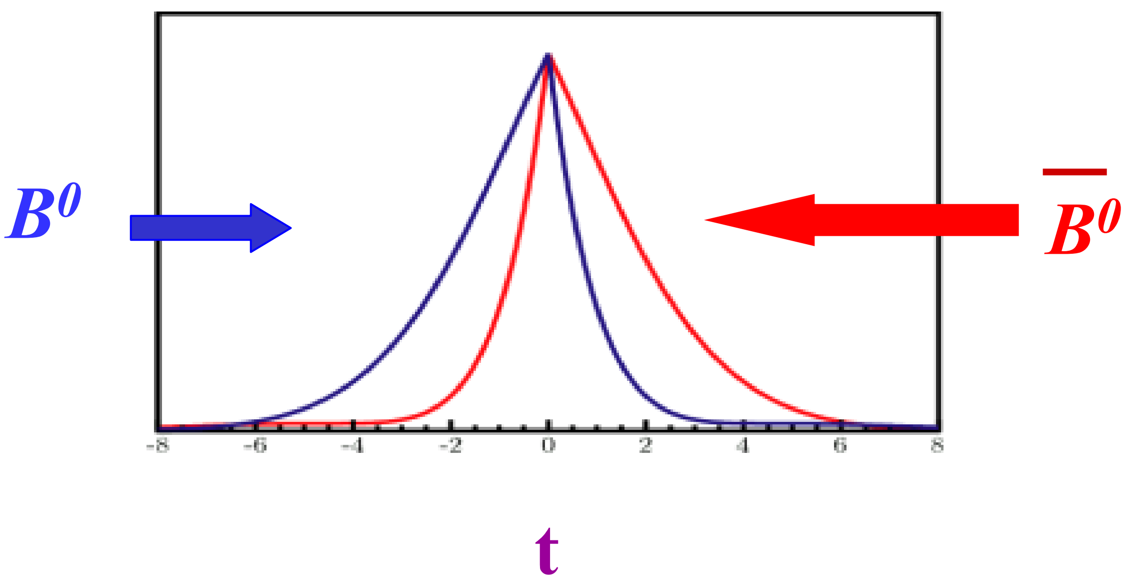


Mixing-induced CPV asymmetry

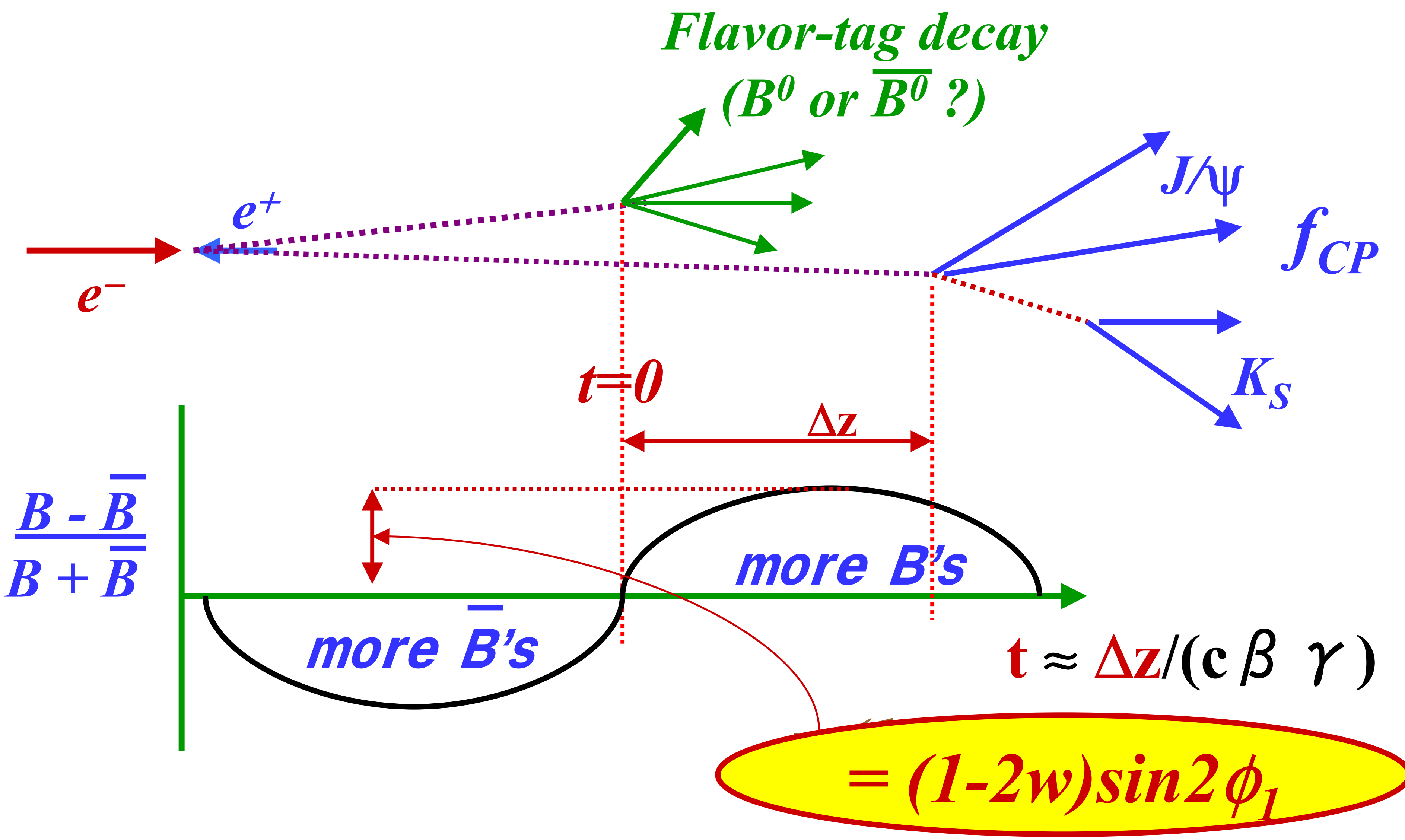
$\xi_f = \pm 1$ *for* $CP = \pm 1$

$$A(t) \equiv \frac{\Gamma(\overline{B}_d^0 \to f_{CP}) - \Gamma(B_d^0 \to f_{CP})}{\Gamma(\overline{B}_d^0 \to f_{CP}) + \Gamma(B_d^0 \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m t$$

a.k.a 2β



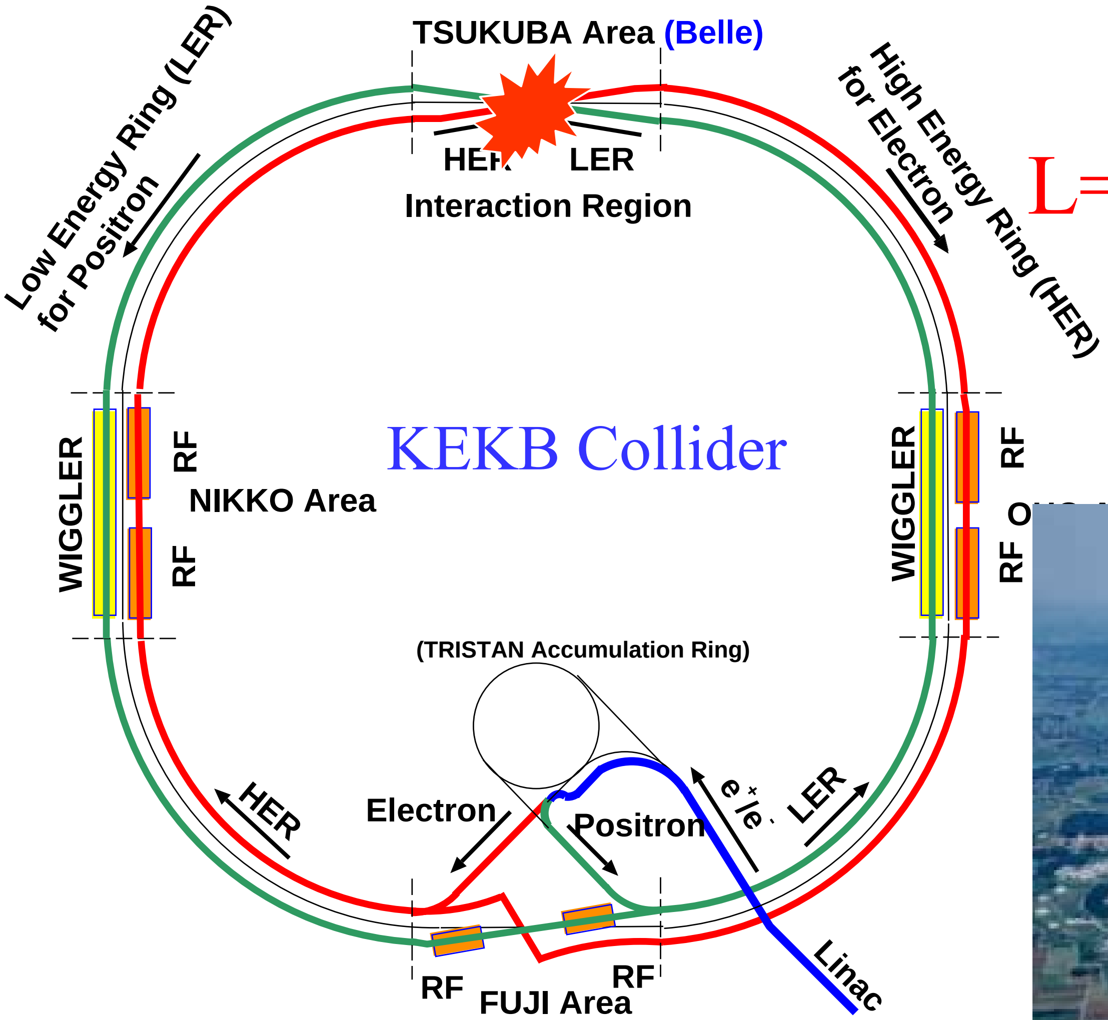
Principle of the Measurement



Requirements for CPV measmts.

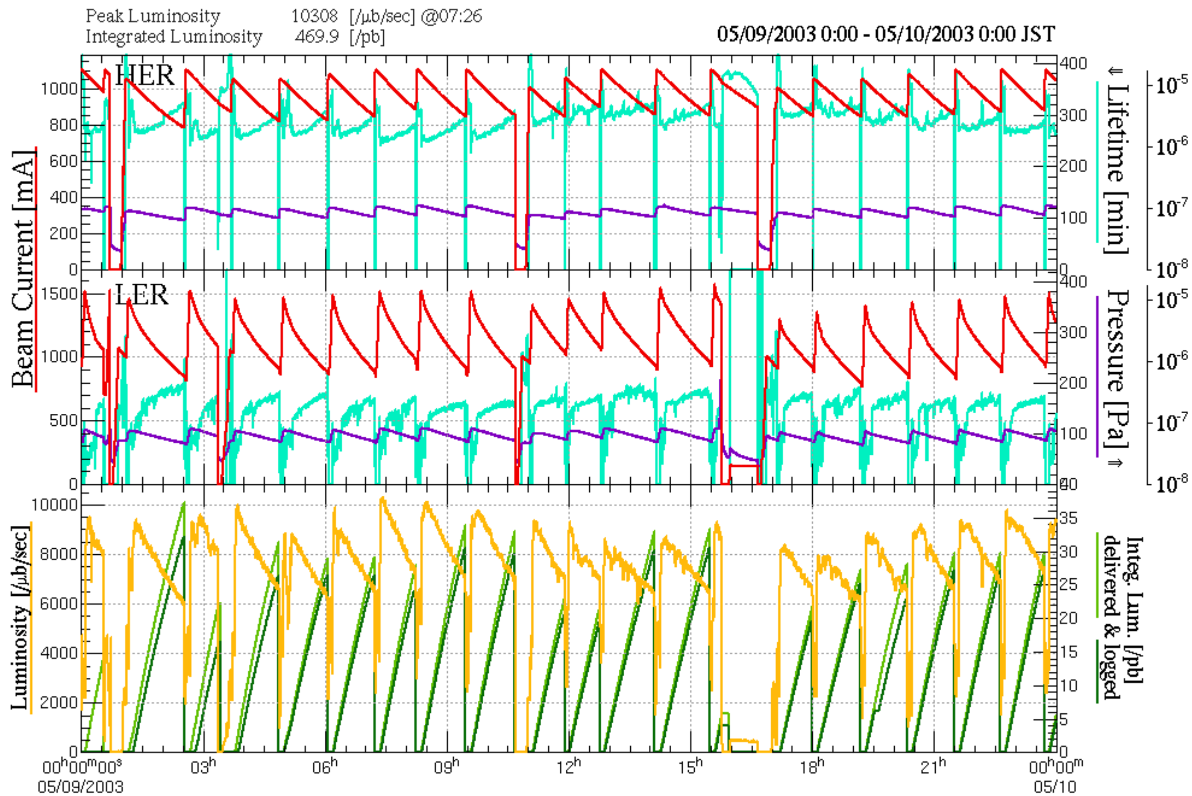
- **Many B mesons** [*Br* (B→f_{CP}) ~ O(10^{-3})]
  - KEKB ➔ 140 fb^{-1} (results today from 78 fb^{-1})
- **Reconstruct+isolate CP eigenstate decays**
  - Kinematic variables for signal +(*cont. bkg suppr+PID*).
- **Tag flavor of the other B**
  - Likelihood based flavor tagging
- **Measure decay-time difference**
  - Asymmetric beam energies, high precision vertexing(Δz)
  - Likelihood fit to the Δt distributions

The KEKB Collider (8 x 3.5 GeV, ±11 mrad X angle)



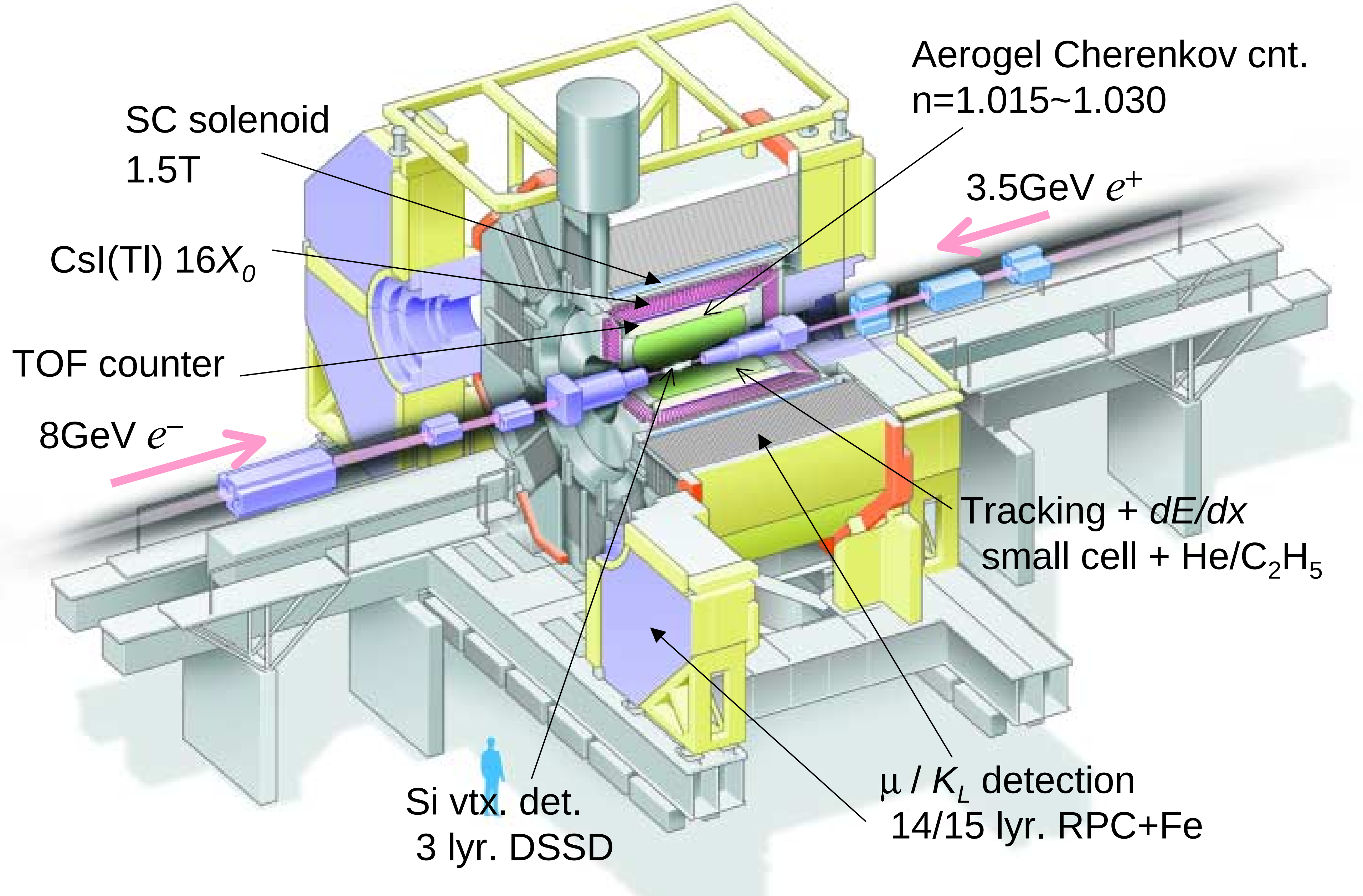
$L=(1.05 \times 10^{34})/cm^2/sec$

$Int(L\,dt)= 140\ fb^{-1}$

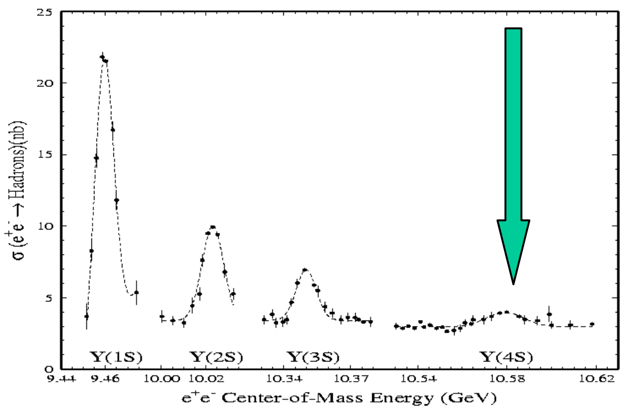


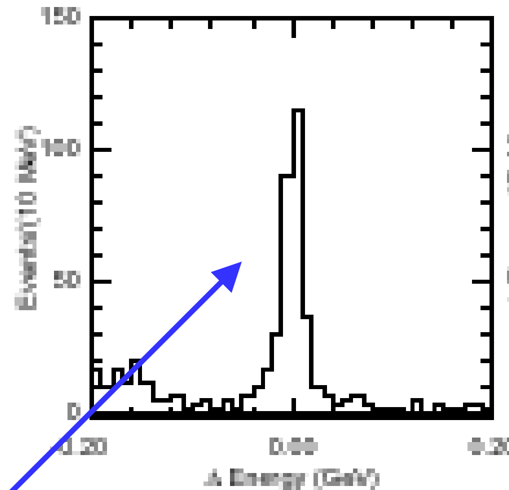
New Daily Record May 13: 595 pb^{-1}/24 hr

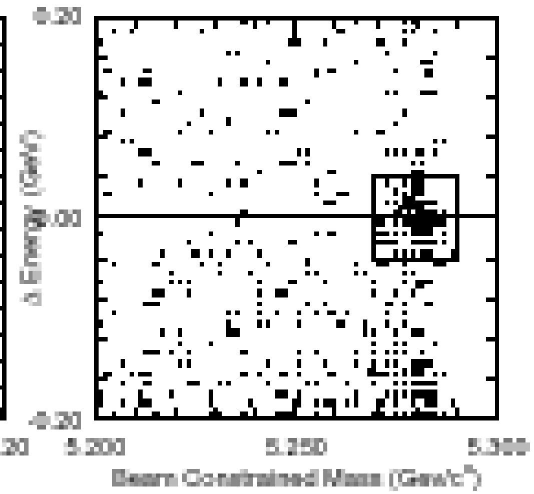
Belle Detector



Kinematic variables for the Υ(4S)



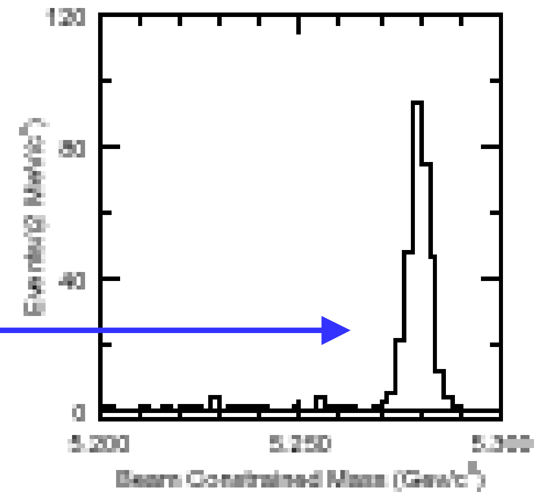




Energy difference:

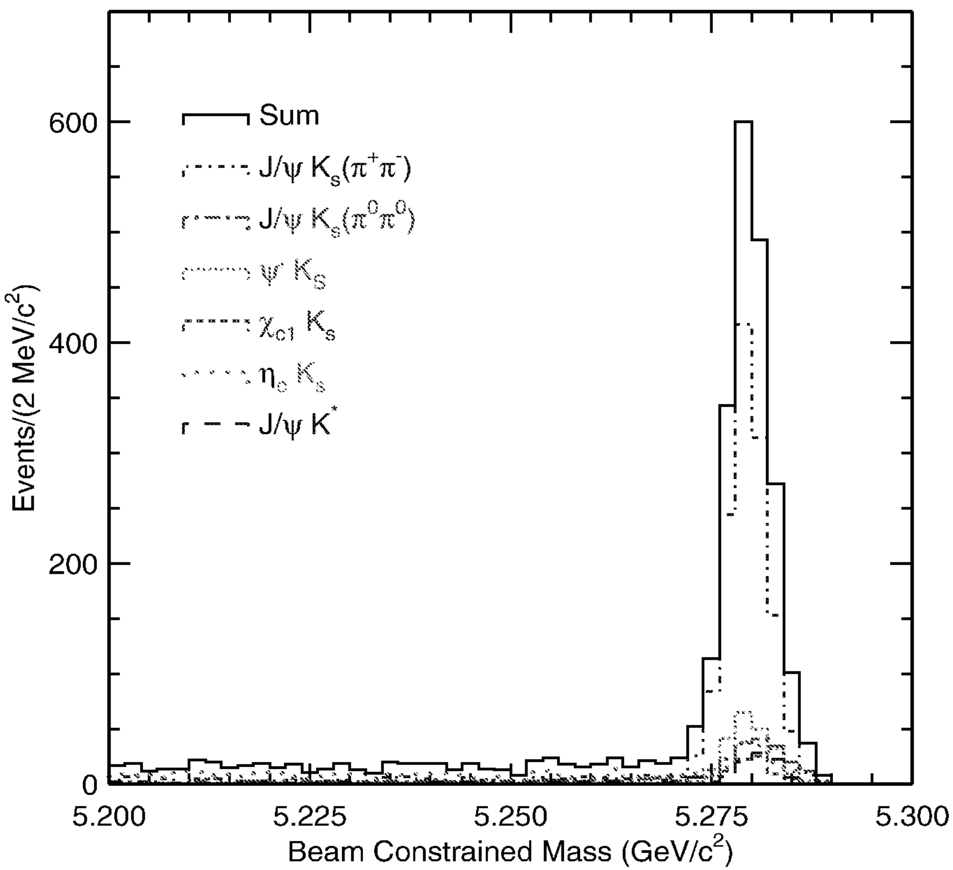
$$\Delta E \equiv E_{J/\psi} + E_{K_S} - E_{CM}/2$$

Beam-constrained mass:



$$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$

Belle: CP eigenstates ($b \to c\bar{c}s$)



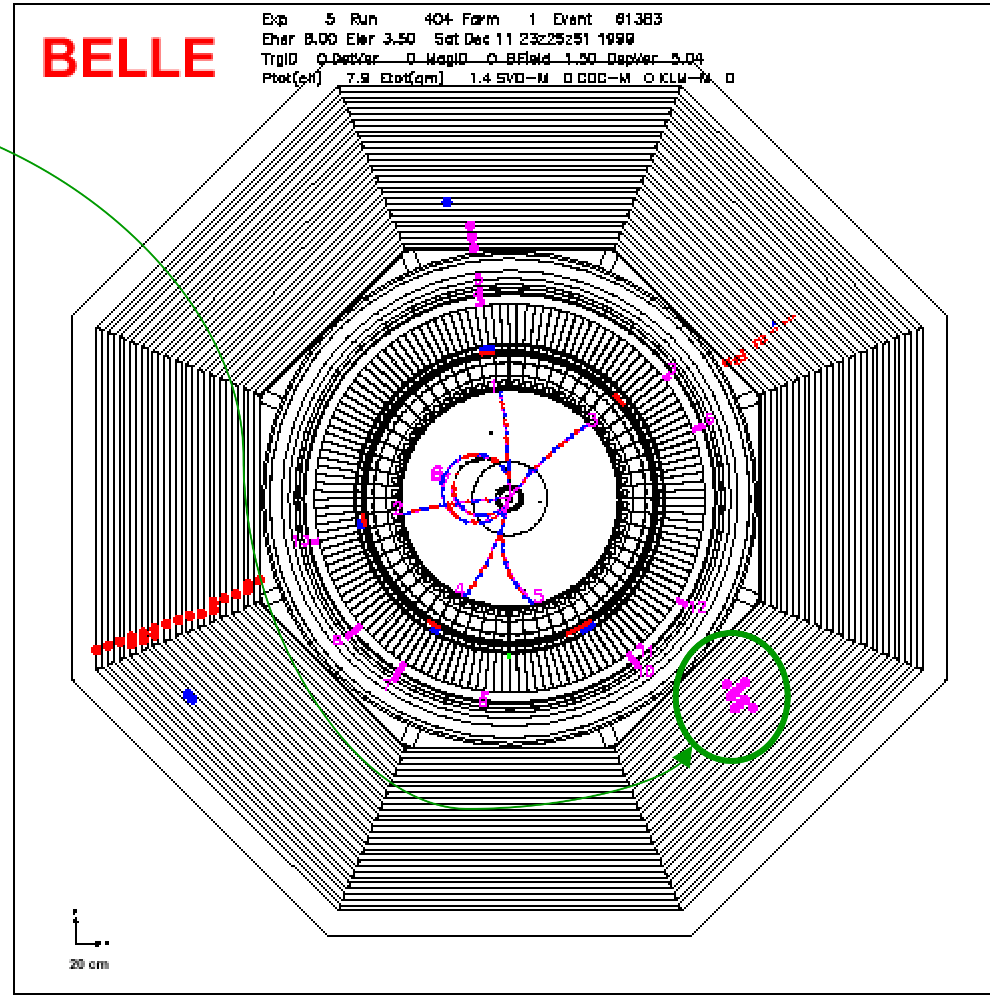
$B \to$	CP	# evts.	S/(S+N)
$J/\psi K_S$ ($K_S \to \pi^+\pi^-$)	odd	1285	0.98
$J/\psi K_S$ ($K_S \to \pi^0\pi^0$)	odd	188	0.82
$\psi(2S)K_S$ ($\psi(2S) \to l^+l^-$)	odd	91	0.96
$\psi(2S)K_S$ ($\psi(2S) \to \pi^+\pi^- J/\psi$)	odd	112	0.91
$\chi_{c1} K_S$ ($\chi_{c1} \to \gamma J/\psi$)	odd	77	0.96
$\eta_c K_S$ ($\eta_c \to K_S K^+\pi^-$)	odd	72	0.65
$\eta_c K_S$ ($\eta_c \to K^+K^-\pi^0$)	odd	49	0.73
$\eta_c K_S$ ($\eta_c \to \bar{p}p$)	odd	21	0.94
$J/\psi K^{*0}$ ($K^{*0} \to K_S \pi^0$)	81% even 19% odd	101	0.92
total		1996	0.94
$J/\psi K_L$	even	1330	0.63
total		3326	

2958 events are used in the fit.

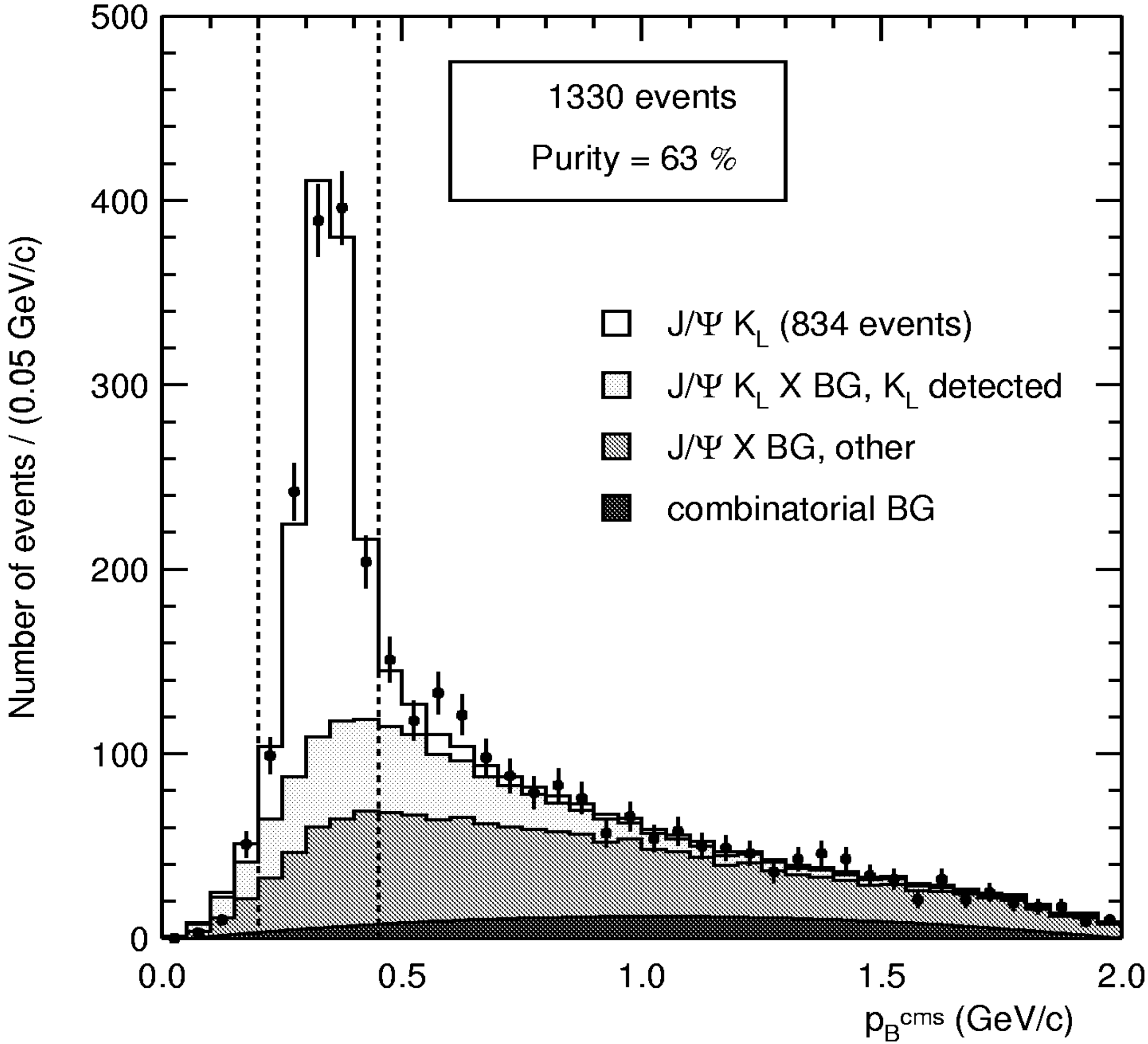
hep-ex/020825, PRD 66, 071102(2002)

Example of a $B^0 \to J/\psi\ K_L$ Decay

1) $J/\psi \to l^+ l^- + K_L$
2) Assume $B \to J/\psi\ K_L$:
   compute $\vec{P}_{KL}$
3) Remove reconstructed
   $B \to J/\psi\ K$, $J/\psi\ K^*$, …
4) Cut on a likelihood
   based on kinematical
   and shape quantities
5) Plot $P^*_B = |\vec{P}_{J/\psi} + \vec{P}_{KL}|$



Belle: $B^0 \rightarrow \psi K_L$ signal



Flavor-tag the other B meson

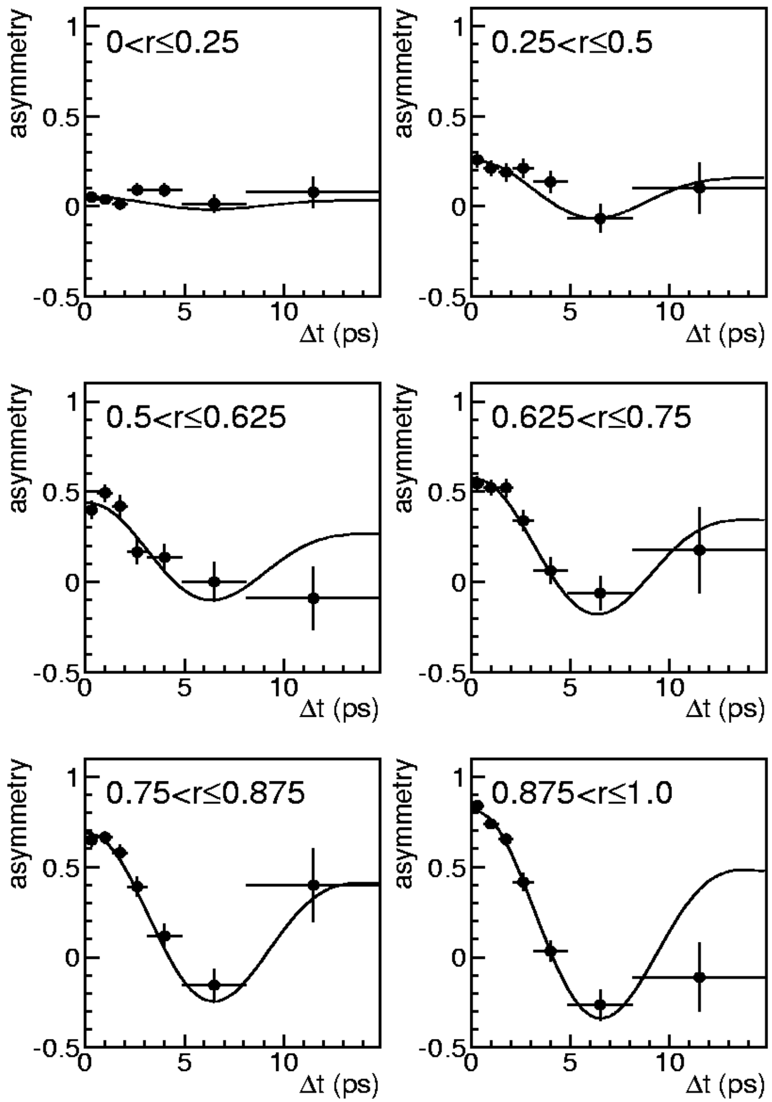
Use *inclusive* flavor-specific properties:

- ***Inclusive Leptons:***
  - ***high-p*** l^- — $b \rightarrow c\, l^- \nu$
  - ***intermed-p*** l^+ — $\quad \hookrightarrow s\, l^+ \nu$
- ***Inclusive Hadrons:***
  - ***high-p*** π^+ — $B^0 \rightarrow D^{(*)-} \pi^+,\ D^{(*)-} \rho^+$, ***etc.***
  - ***intermed-p*** K^+ — $\quad \hookrightarrow K^+ X,\quad \rho^+ \hookrightarrow \pi^+ \pi^0$
  - ***low-p*** π^- — $\quad \hookrightarrow \overline{D}^0 \pi^-$

⇒ Also take into account correlations.

Effective $\varepsilon_{eff} = 28.8 \pm 0.6\%$

Tagging Performance illustrated with $B \rightarrow D^{*+} l^- \upsilon$



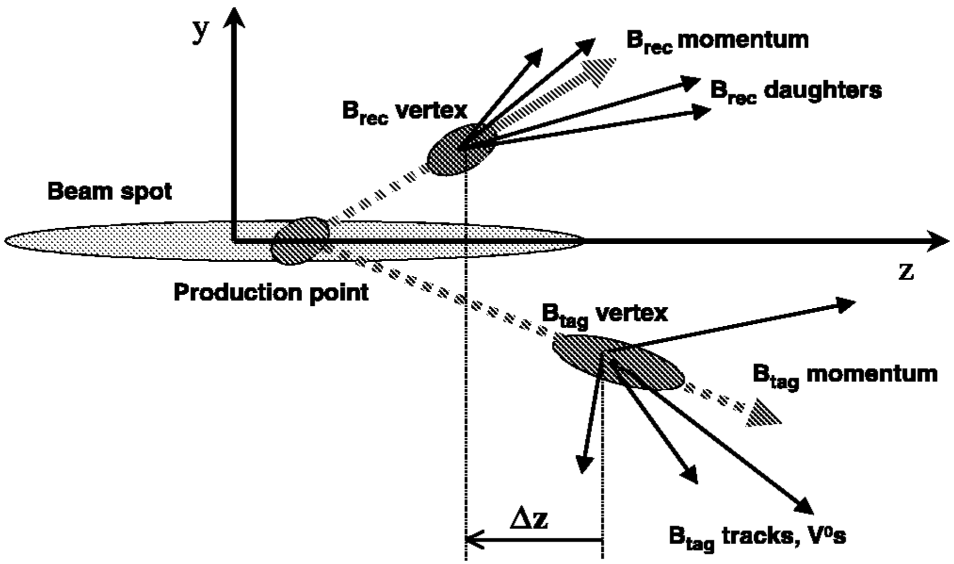
(OF-SF)/(OF+SF)

~(1-2 w)cos(Δm t)

r		w	ε_{eff}
$r > 0.875$	0.136	0.020±0.006	$0.126^{+0.003}_{-0.004}$
$0.75 < r < 0.875$	0.094	0.112±0.009	0.056 ± 0.003
$0.625 < r < 0.75$	0.122	$0.160^{+0.009}_{-0.008}$	0.056 ± 0.003
$0.5 < r < 0.625$	0.104	0.228±0.010	0.031 ± 0.002
$0.25 < r < 0.5$	0.146	0.336±0.009	0.016 ± 0.002
$r < 0.25$	0.398	0.458±0.006	0.003 ± 0.001
Total	1.0		0.288±0.006

$$\Delta t = (z_{TAG} - z_{CP}) / \gamma \beta$$

Beam spot: 110 μm x 5 μm x 0.35 cm

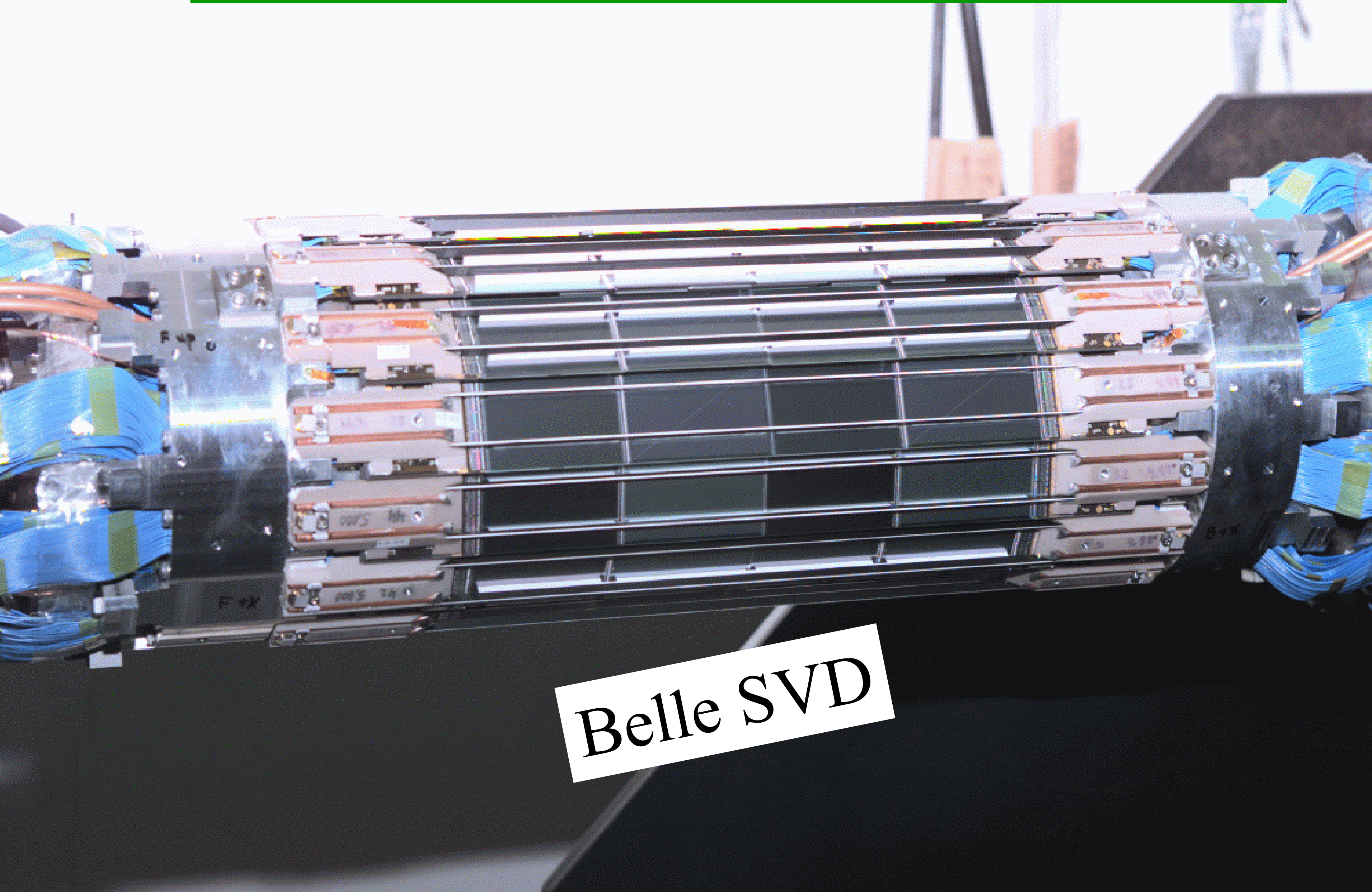


Belle uses double-sided silicon strip detectors and a small radius beampipe (r=2cm) to measure Δz.

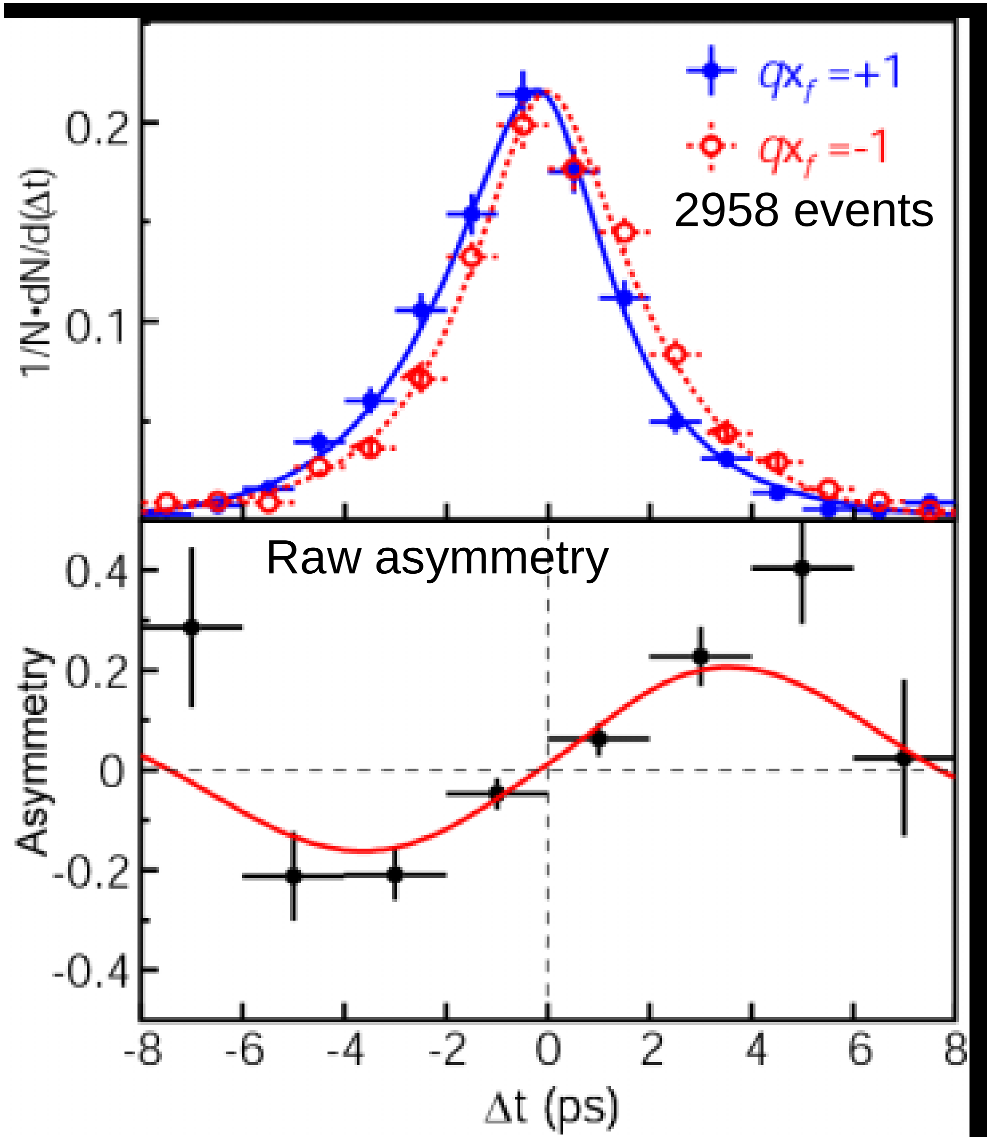
KEKB: 8 x 3.5 GeV : $\beta\gamma = 0.425$

Vertex resolutions: $(\sigma(z_{cp}) = 75\mu m;\ \sigma(z_{tag}) = 140\mu m)$

Measure $(z_{TAG} - z_{CP}) / \gamma \beta$



Precise measurement of $\sin 2\phi_1$ (Belle)



- 78 fb^{-1} (84M $B\overline{B}$)
- 6 $b \to c\bar{c}s$ decay modes ($B \to \Psi K_S$, ΨK_L , $\eta_C K_{S..}$)
- $S_{ccs} = \sin 2\phi_1$

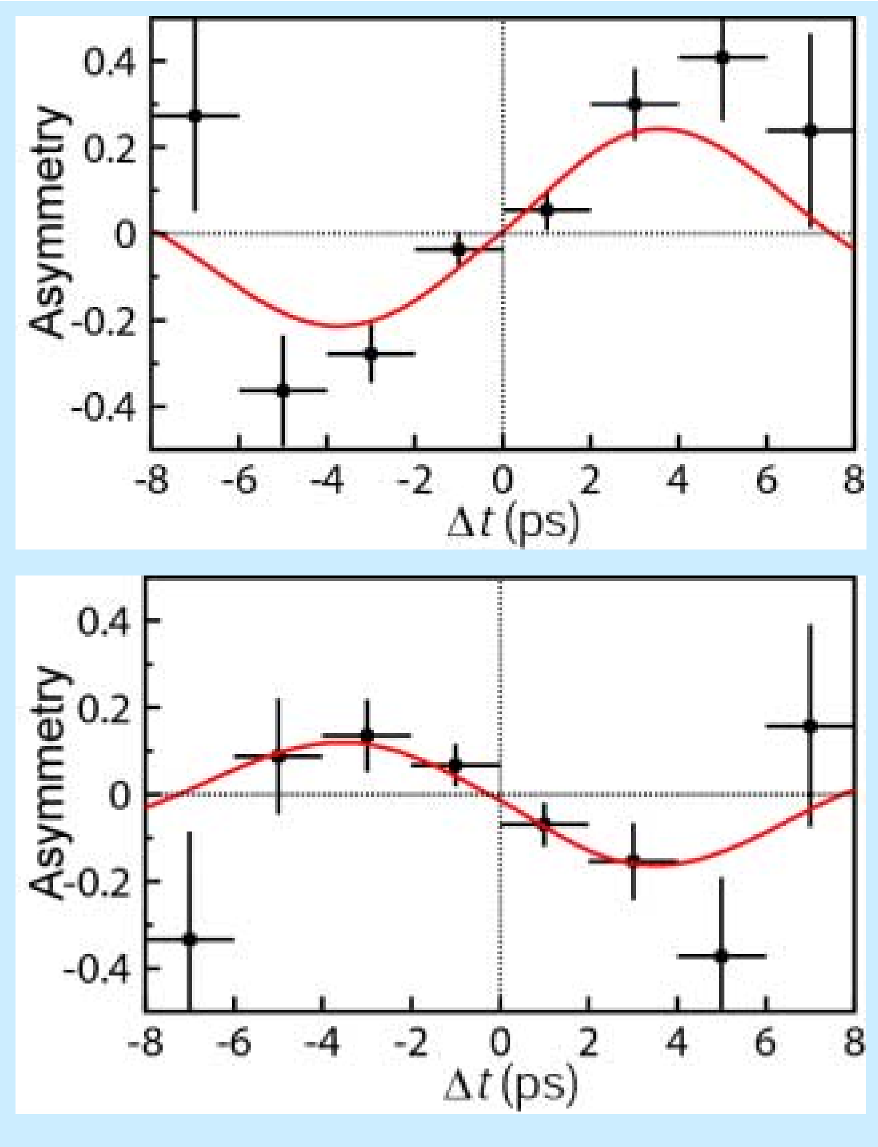
= **0.719±0.074±0.035**

- $|\lambda_{ccs}|$ =0.950±0.049±0.026 *i.e.*, consistent with no direct CPV.

hep-ex/020825, PRD 66, 071102 (2002)

Compare CP odd and CP even (Belle)

Raw asymmetry



CP = -1 sample

$\sin 2\phi_1$

$= 0.716 \pm 0.083$

CP = +1 sample

$(B^0 \rightarrow J/\psi K_L)$

$\sin 2\phi_1$

$= 0.78 \pm 0.17$

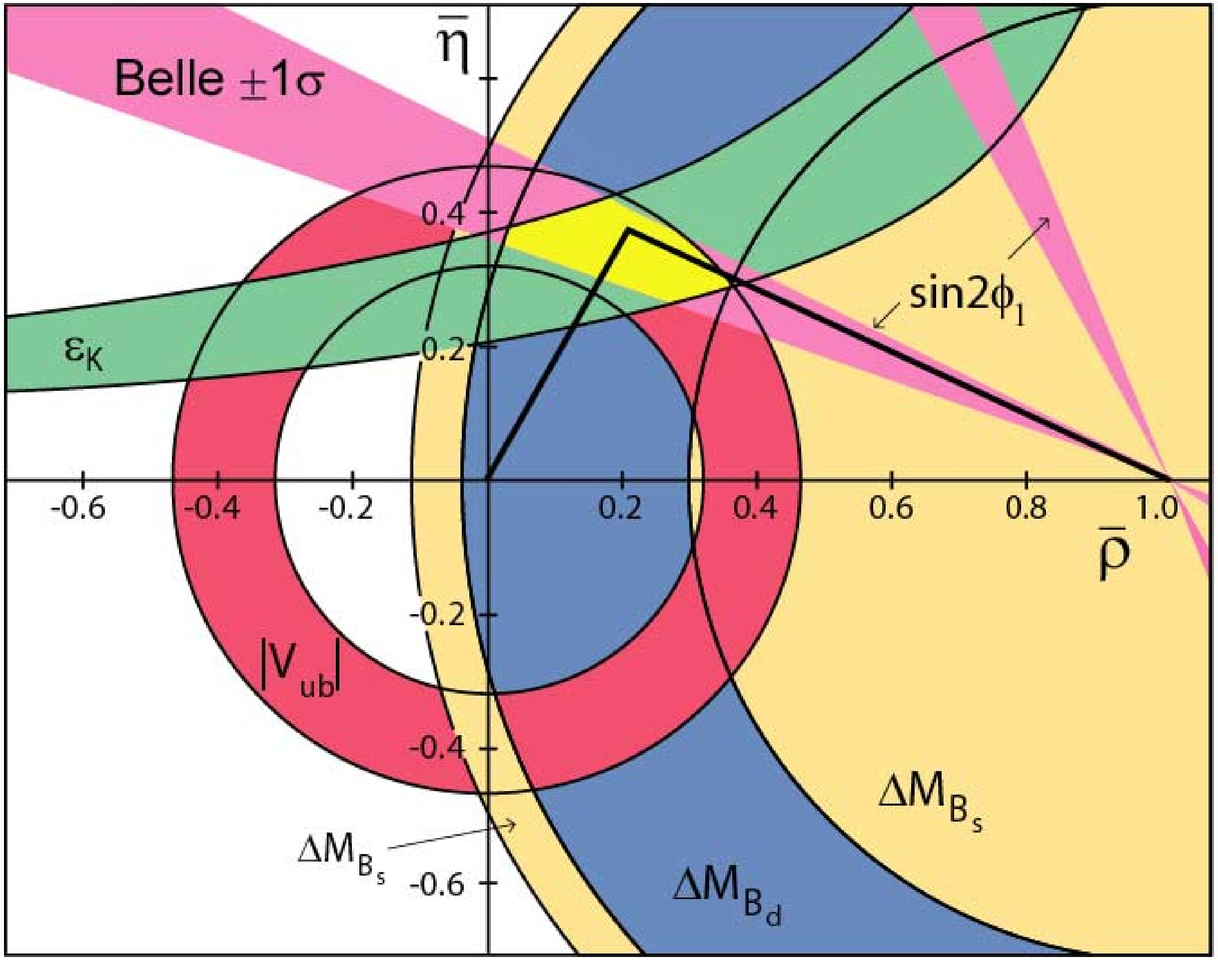
hep-ex/020825, PRD 66,071102 (2002)

Details of Belle's **sin2ϕ_1** measurement

TABLE III. The numbers of candidate events, N_{ev}, and values of $\sin 2\phi_1$ for various subsamples (statistical errors only).

Sample	N_{ev}	$\sin 2\phi_1$
$J/\psi K_S^0(\pi^+\pi^-)$	1116	0.73 ± 0.10
$(c\bar{c})K_S^0$ except $J/\psi K_S^0(\pi^+\pi^-)$	523	0.67 ± 0.17
$J/\psi K_L^0$	1230	0.78 ± 0.17
$J/\psi K^{*0}(K_S^0\pi^0)$	89	0.04 ± 0.63
$f_{tag}=B^0$ $(q=+1)$	1465	0.65 ± 0.12
$f_{tag}=\bar{B}^0$ $(q=-1)$	1493	0.77 ± 0.09
$0<r\leqslant0.5$	1600	1.27 ± 0.36
$0.5<r\leqslant0.75$	658	0.62 ± 0.15
$0.75<r\leqslant1$	700	0.72 ± 0.09
data before 2002	1587	0.78 ± 0.10
data in 2002	1371	0.65 ± 0.11
All	2958	0.72 ± 0.07

Belle's sin(2φ_1) measurement in the ρ-η plane



sin2ϕ_1

=0.719±0.074±0.035

Belle July, 2002

PDG2002 (http://pdg.lbl.gov/2002/kmmixrpp)

Status/history of results for $\sin(2\varphi_1)$[$\sin(2\beta)$]

Belle 2001: $\sin(2\varphi_1) = 0.99 \pm 0.14 \pm 0.06$

Babar 2001: $\sin(2\varphi_1) = 0.59 \pm 0.14 \pm 0.05$

First signals for CPV outside of the kaon sector

Belle 78 fb^{-1} : $\sin(2\varphi_1) = 0.719 \pm 0.074 \pm 0.035$

Babar 81 fb^{-1}: $\sin(2\varphi_1) = 0.741 \pm 0.067 \pm 0.033$

Now becoming a precision measurement

Summer of 2001

Belle:

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Observation of Large CP Violation in the Neutral B Meson System

We present a measurement of the standard model CP violation parameter $\sin 2\phi_1$ based on a 29.1 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson is fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, or $J/\psi K^{*0}$ decay and the flavor of the accompanying B meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we determine $\sin 2\phi_1 = 0.99 \pm 0.14(\mathrm{stat}) \pm 0.06(\mathrm{syst})$. We conclude that we have observed CP violation in the neutral B meson system.

BaBar:

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Observation of CP Violation in the B^0 Meson System

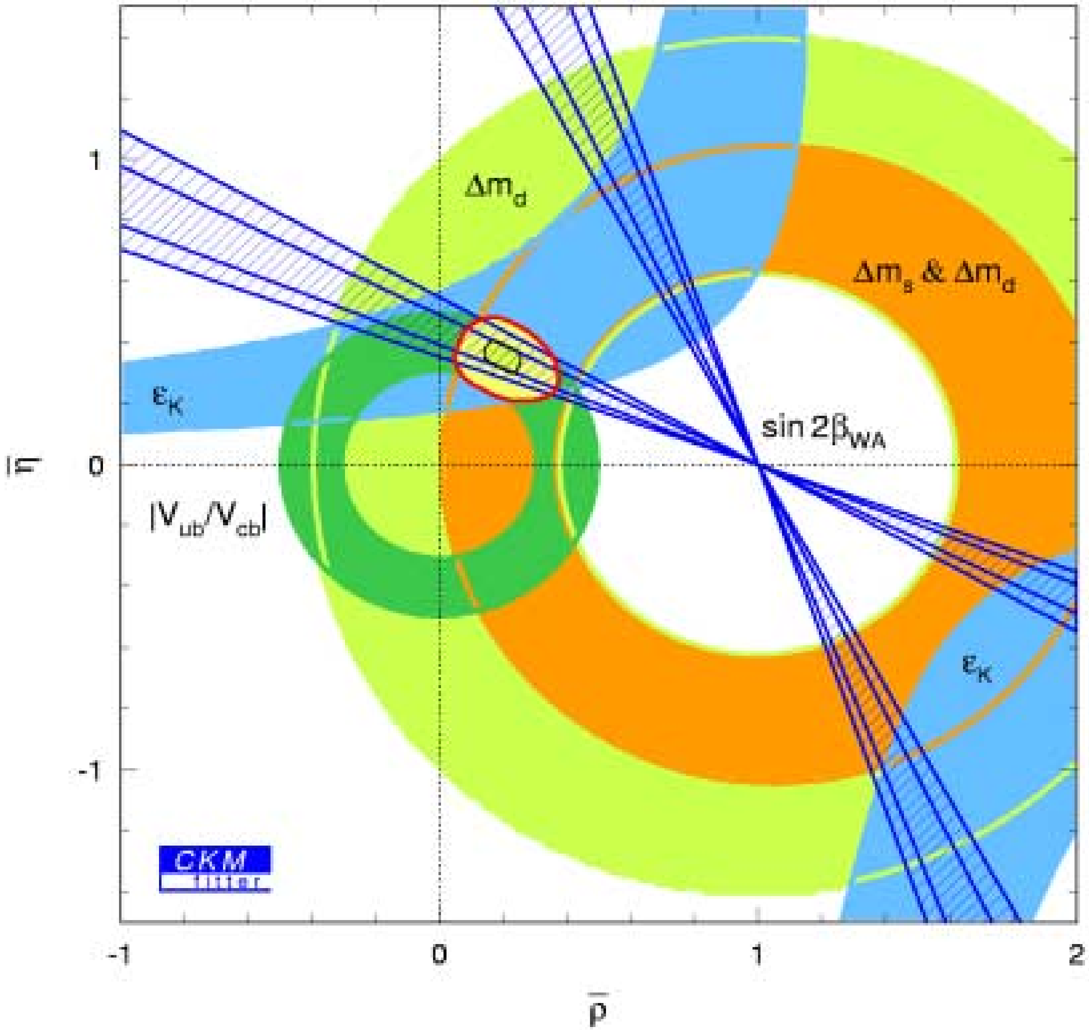
We present an updated measurement of time-dependent CP-violating asymmetries in neutral B decays with the *BABAR* detector at the PEP-II asymmetric B Factory at SLAC. This result uses an additional sample of $\Upsilon(4S)$ decays collected in 2001, bringing the data available to 32×10^6 $B\overline{B}$ pairs. We select events in which one neutral B meson is fully reconstructed in a final state containing charmonium and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the CP-violating asymmetry, which in the standard model is proportional to $\sin 2\beta$, is derived from the decay time distributions in such events. The result $\sin 2\beta = 0.59 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ establishes CP violation in the B^0 meson system. We also determine $|\lambda| = 0.93 \pm 0.09(\mathrm{stat}) \pm 0.03(\mathrm{syst})$, consistent with no direct CP violation.

Contributions to the systematic error in sin(2φ_1)

Table 8: Contributions to the systematic error in sin2β.

source	*BABAR*	Belle
vertexing	0.014	0.022
dilutions	0.012	0.015
resolution function	0.009	0.014
physics	0.005	0.007
$J/\psi\, K_L^0$ background	0.015	0.010
signal & background	0.018	0.006
fit bias	0.013	0.011
total	0.034	0.035

Current Belle and BaBar Results for sin(2φ_1)



$\sin 2\phi_1$ (Belle)

$=0.719 \pm 0.074 \pm 0.035$

$\sin 2\phi_1$ (BaBar)

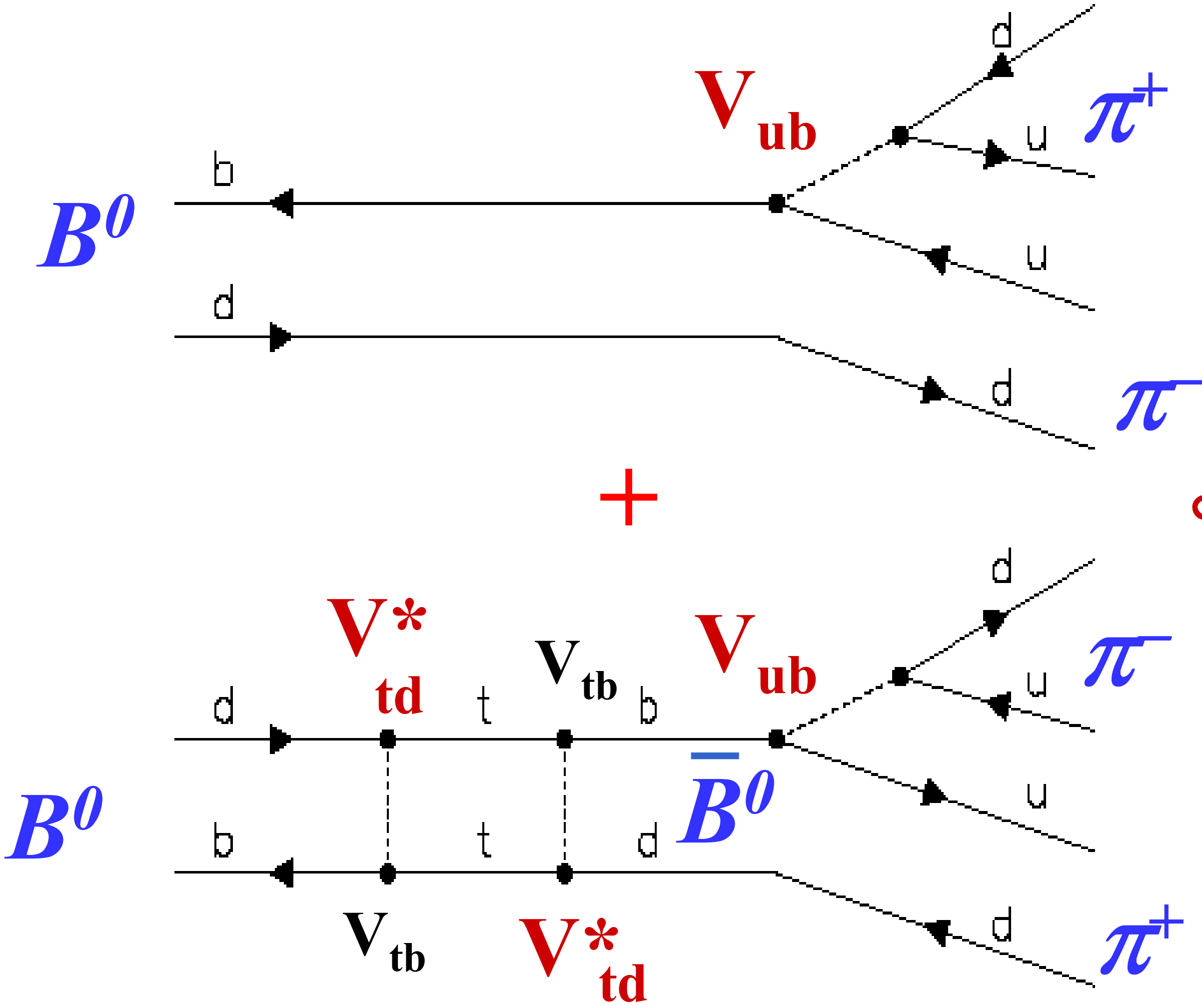
$=0.741 \pm 0.067 \pm 0.033$

$\sin 2\phi_1$ (World Av.)

$=0.734 \pm 0.055$

B→$\pi^+ \pi^-$ CPV CONTROVERSY

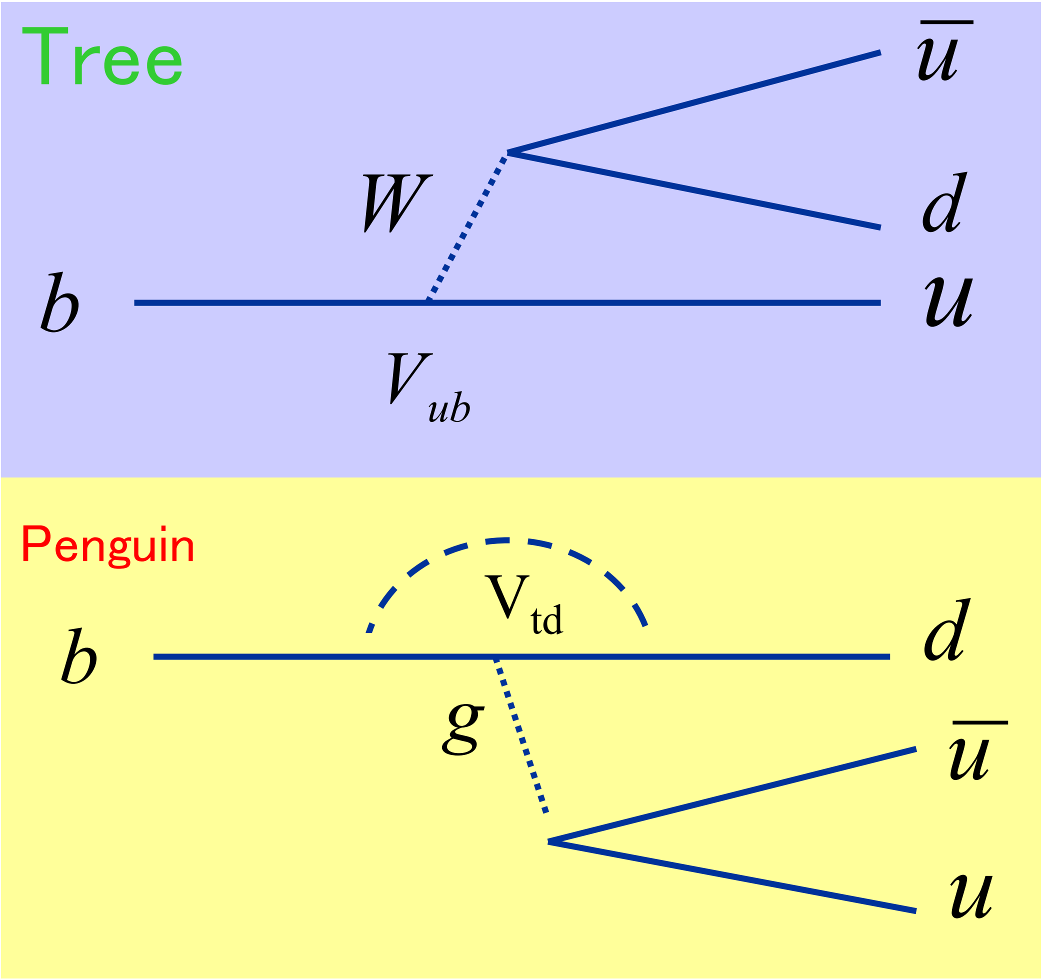
Next: $\phi_2(\alpha)$ from $B \to |f_{cp}\rangle = \pi^+\pi^-$



$\propto V^{*2}_{td} V^2_{ub} \propto \sin 2\phi_2$

(a.k.a sin 2α)

"*Penguin Pollution*" in $B \rightarrow \pi^+ \pi^-$



+ Mixing

Isospin analysis:

Isolate the penguin

Direct CPV asymmetry

- Asymmetry in B decay rates

$$A_{dir} \equiv \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)}$$

$$= \frac{2r \sin\phi \sin\delta}{1 + r^2 + 2r\cos\phi\cos\delta}$$

$$r = |P|/|T|, \phi = weak\ \ phase\ diff$$

$$\delta = strong\ \ phase\ diff$$

- The direct CP asymmetry (A_{dir}) can be significant if the b→d penguin (P) and b→u tree(T) amplitudes are comparable.

Observables: $S_{\pi\pi}$ and $A_{\pi\pi}$

$$S_{\pi\pi} = \frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1} = \sqrt{1-A_{\pi\pi}{}^2}\ \boxed{\sin 2(\phi_2+\theta)}$$

$$A_{\pi\pi} = \frac{|\lambda|^2-1}{|\lambda|^2+1} = \frac{|\bar{A}_{+-}|^2-|A_{+-}|^2}{|\bar{A}_{+-}|^2+|A_{+-}|^2}$$

DCPV asymmetry

λ is a complex parameter: the product of p/q and the ratio of the amplitudes for B^0 and $\overline{B}^0$ decay to $\pi^+\pi^-$

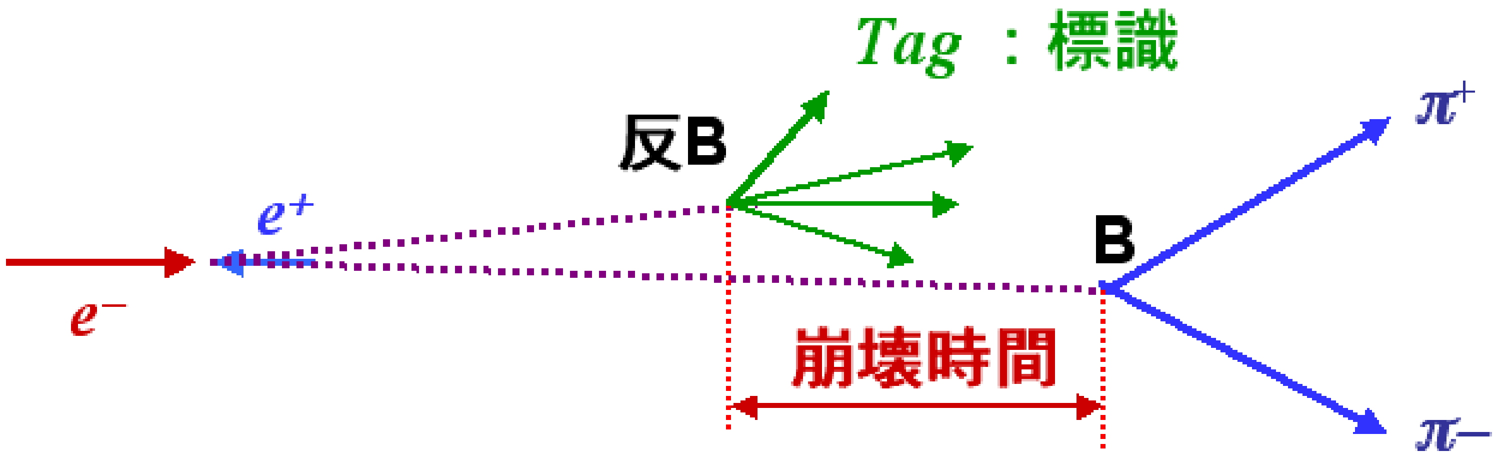
N.B. Notational convention, $C_{\pi\pi} = - A_{\pi\pi}$

Measurement of CPV asymmetries

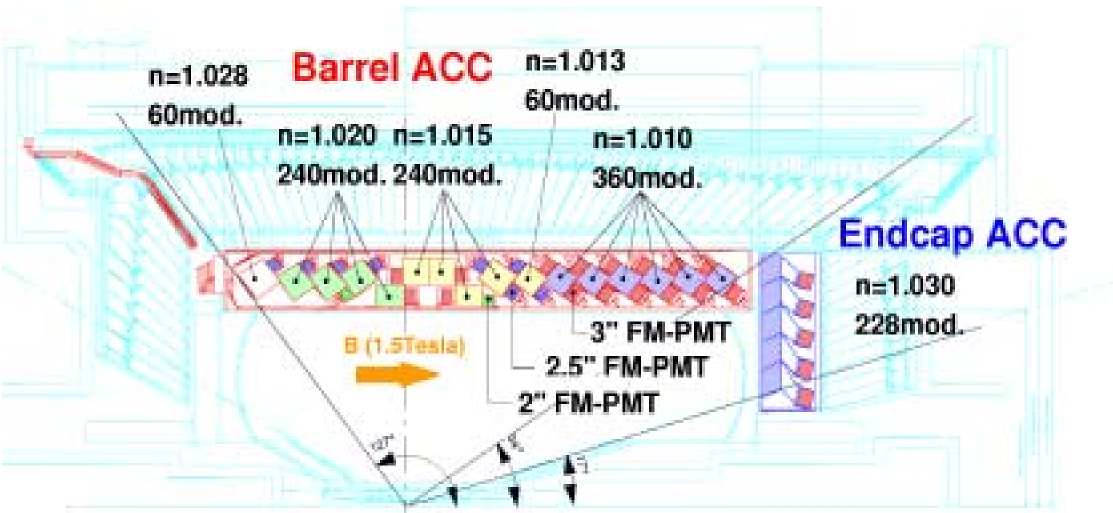
$$P_{\pi\pi}(B \to \pi^+\pi^-;\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}[1+q\cdot\{A_{\pi\pi}\cos(\Delta m\Delta t)$$

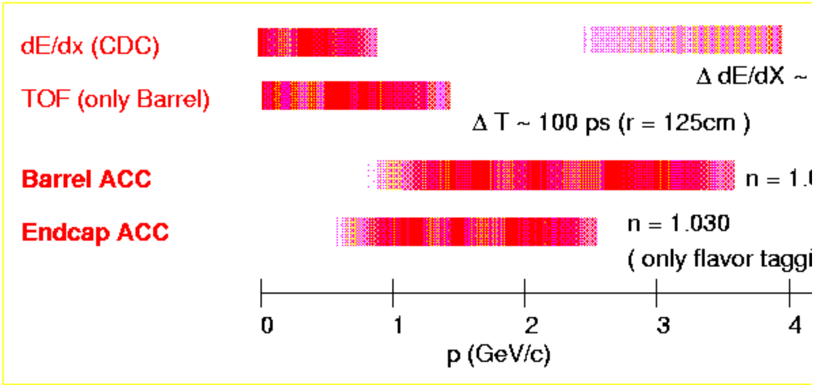
$$+ \ S_{\pi\pi}\sin(\Delta m\Delta t)\}]$$

with q=±1



Particle Identification (Belle)





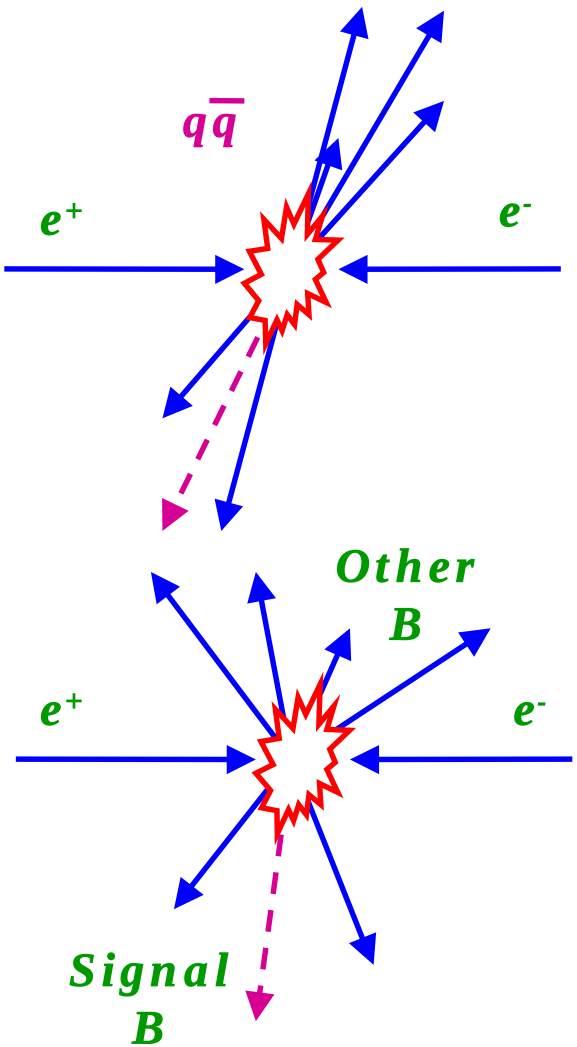
For $B \rightarrow \pi^+ \pi^-$,

eff: $\varepsilon_\pi = 91\%$

fake: $\varepsilon_K = 10.3\%$

$(10.0 \pm 0.2)\ K^-$, $(10.6 \pm 0.2)\ K^+$

Continuum suppression (Idea)



Collimated, jetlike

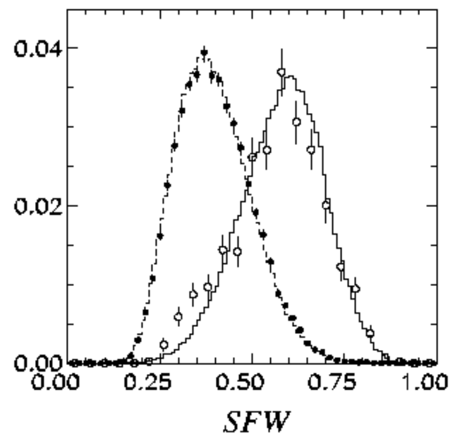
$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$

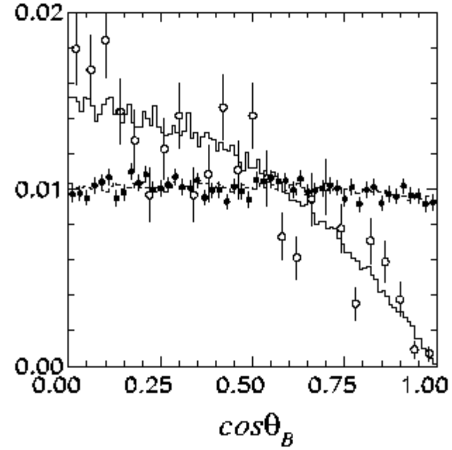
Small energy release

spherical

Continuum suppression (Belle)

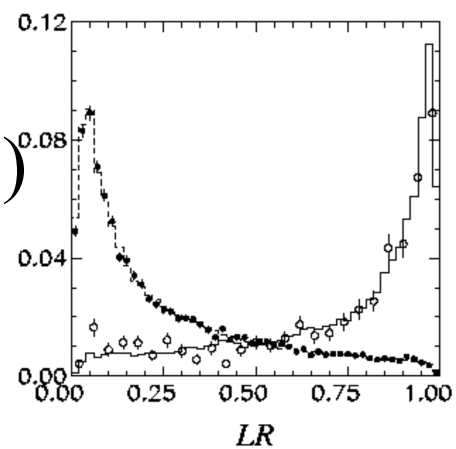
SFW

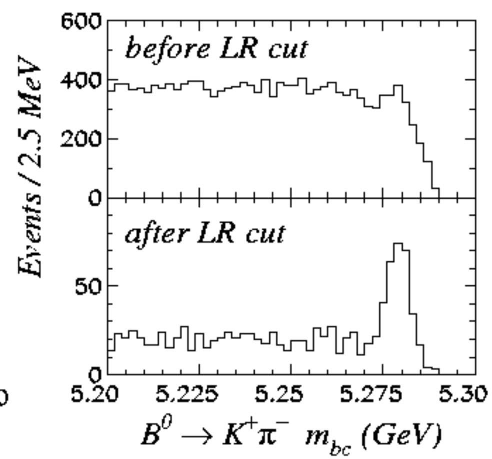




Cos θ_B

$L_S/(L_S + L_B)$

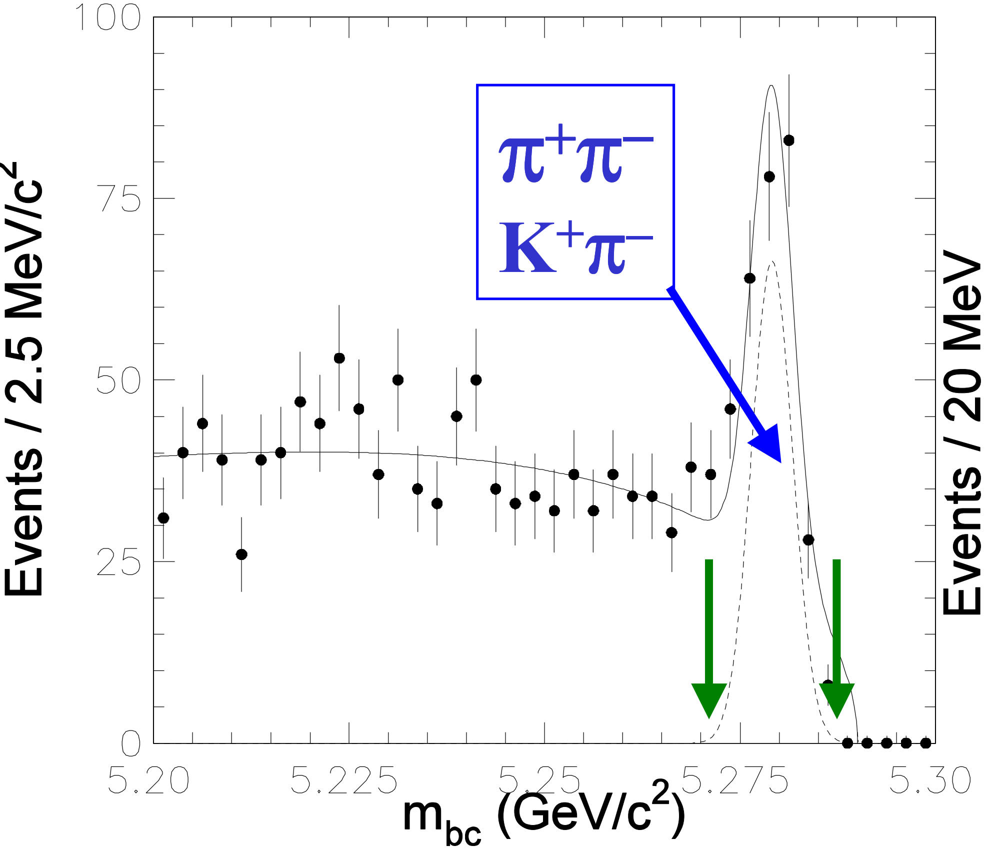




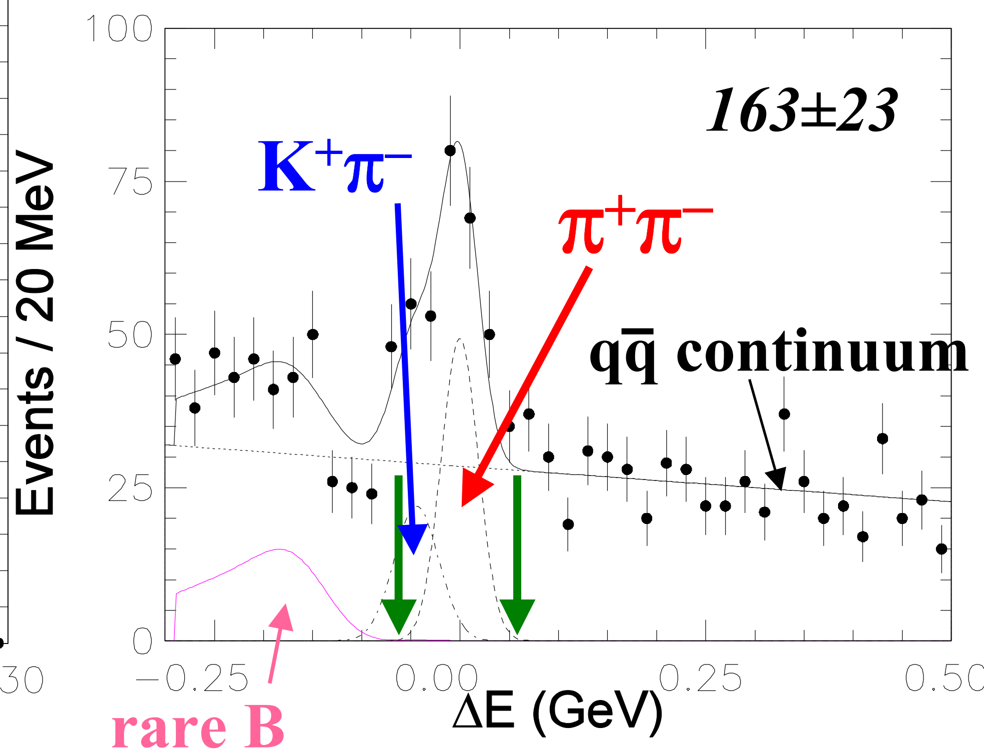
$eff(B\overline{B})$=53%
$eff(q\overline{q})$= 5%

Kinematic variables for $B \rightarrow \pi^+ \pi^-$

Beam-constrained mass (M_{bc})



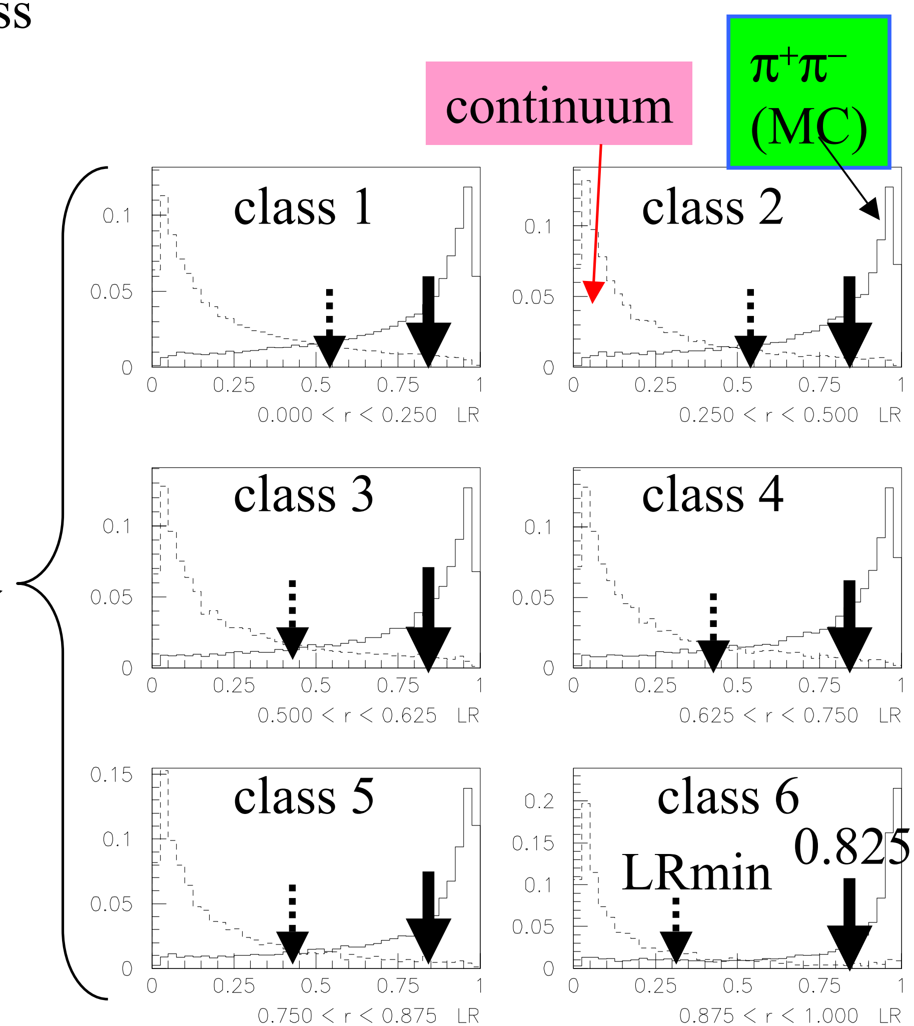
energy difference (ΔE)



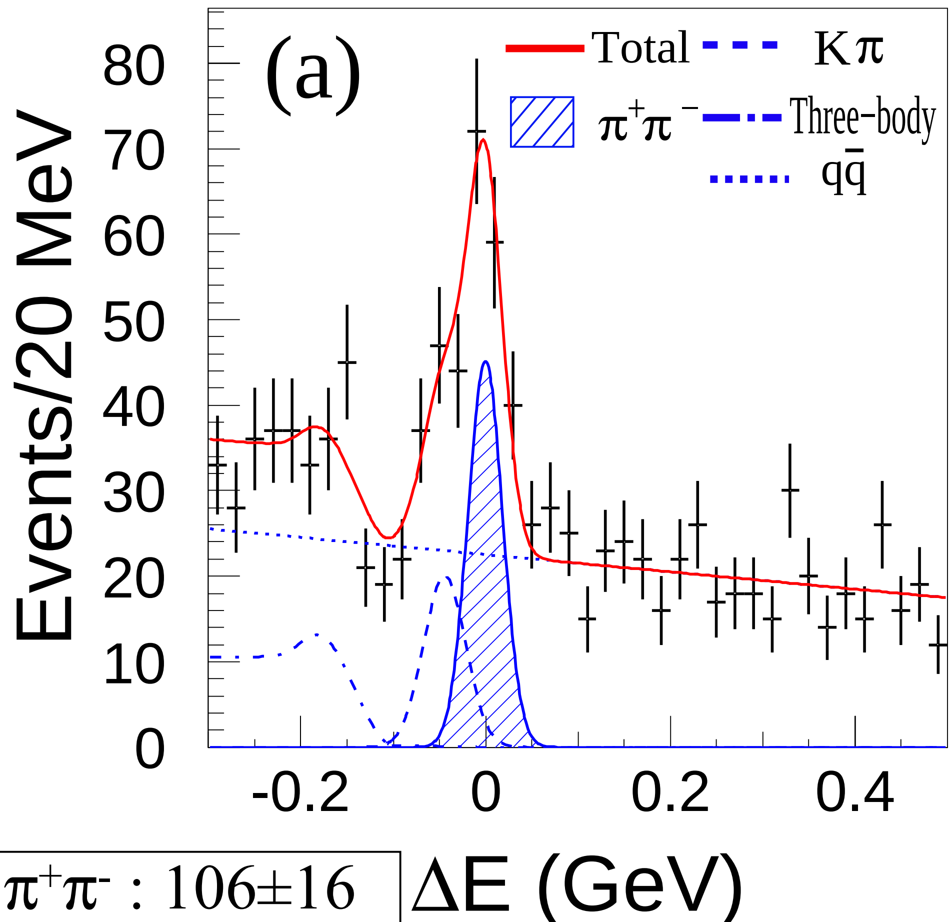
Event shape cut depends on flavor tag category.

- Select 2 regions for each flavor tag class
  - LR > 0.825
  - LRmin < LR ≤ 0.825

$$LR = \frac{L_S}{L_S + L_{q\bar{q}}}$$



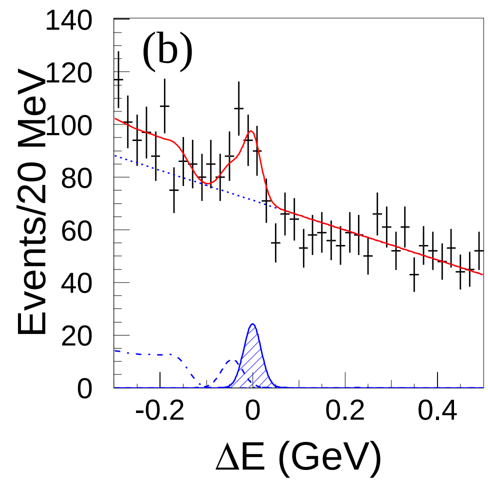
$B \to \pi^+ \pi^-$ Data Sample



LR > 0.825

$\pi^+\pi^-$	: 106±16
Kπ	: 41 ±10
qq	: 128 ±6
total	: 275

LRmin < LR ≤ 0.825



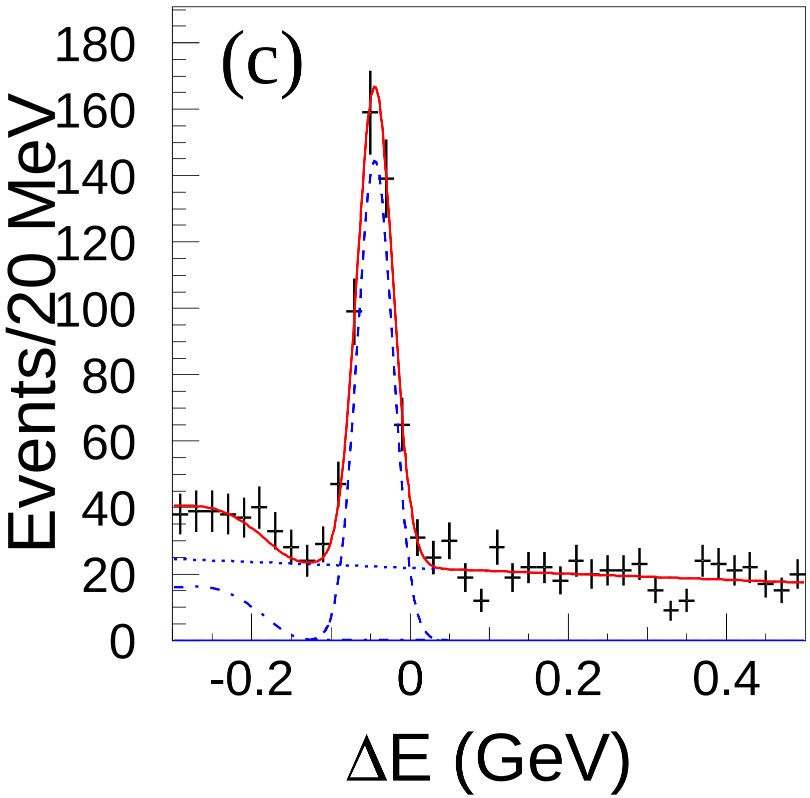
$\pi^+\pi^-$:	57 ±8
Kπ :	22 ±6
qq	: 406 ±17
total	: 485

$B \rightarrow K^- \pi^+$ *Control Sample*

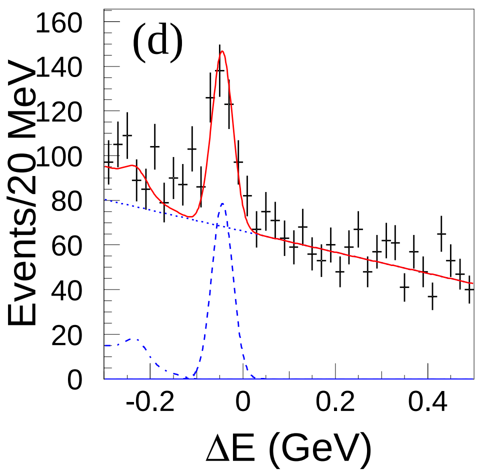
Positively-identified kaons

(ε_K=84% ; ε_π =5%)

LR > 0.825

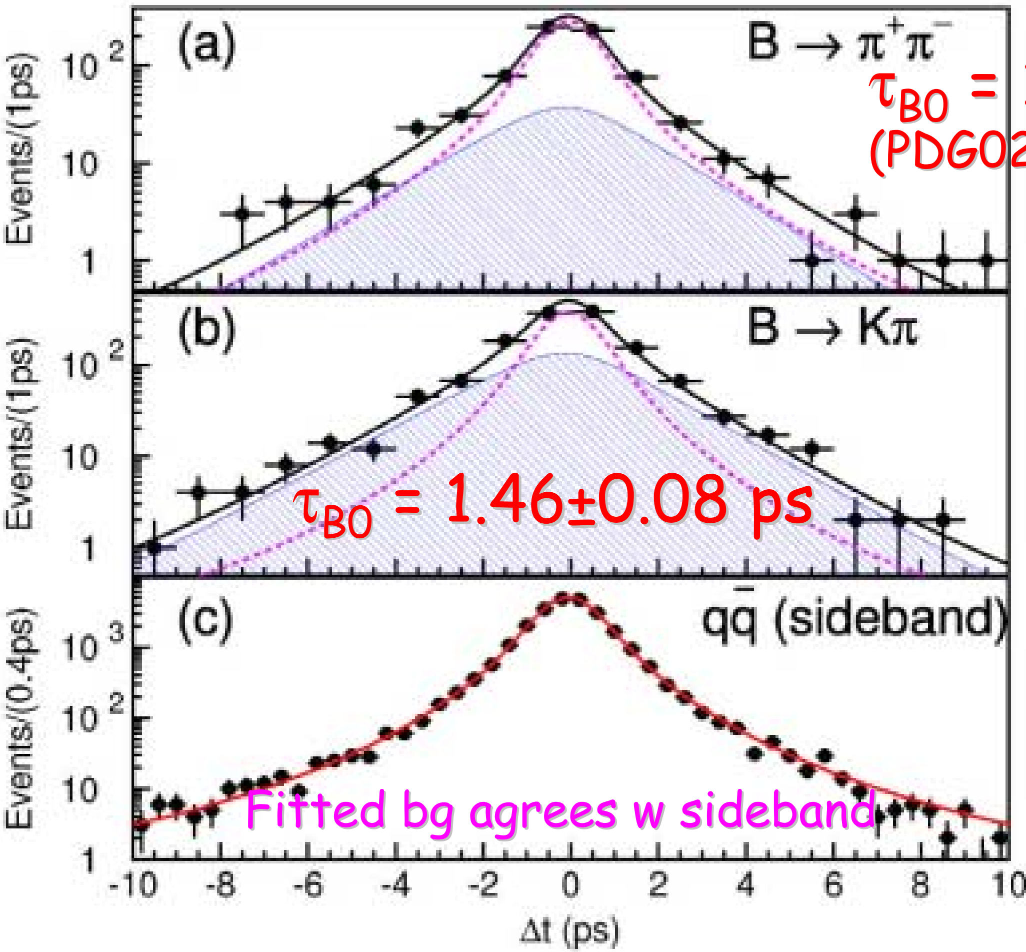


LRmin < LR ≤ 0.825



total $K\pi$ yield: 610 events

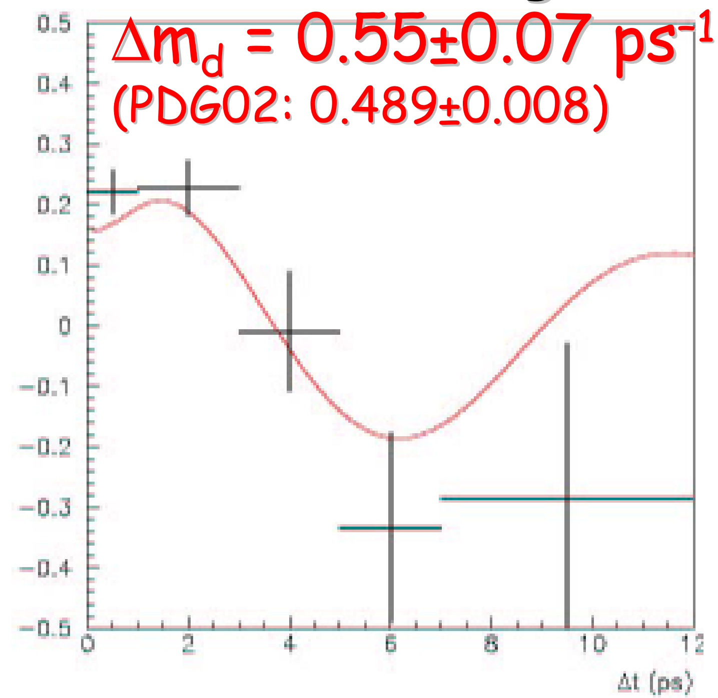
Tests: Lifetime and Mixing Measurements



τ_{B0} = 1.42±0.14 ps
(PDG02: 1.542±0.016)

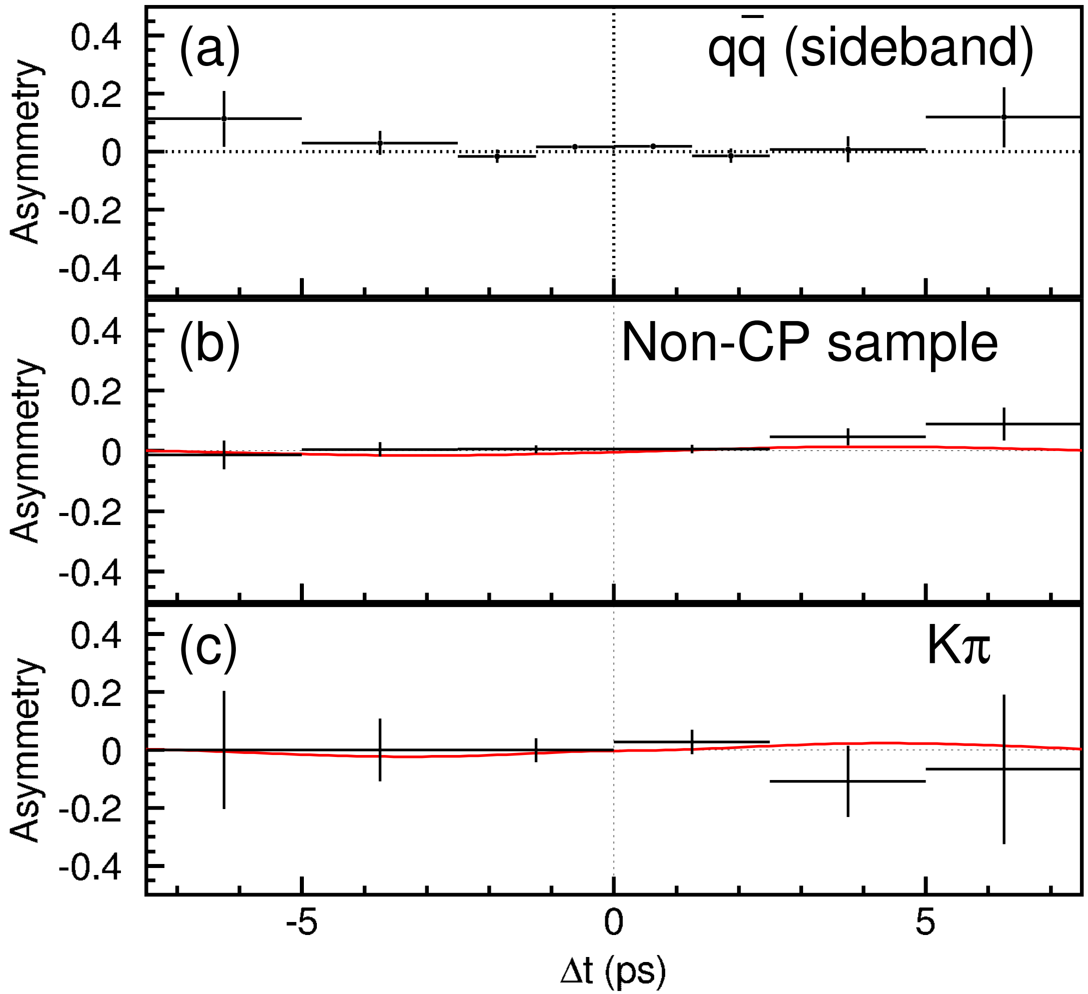
τ_{B0} = 1.46±0.08 ps

B^0->$K^+\pi^-$ mixing



Δm_d = 0.55±0.07 ps^{-1}
(PDG02: 0.489±0.008)

Tests with Control Samples



No asymmetry

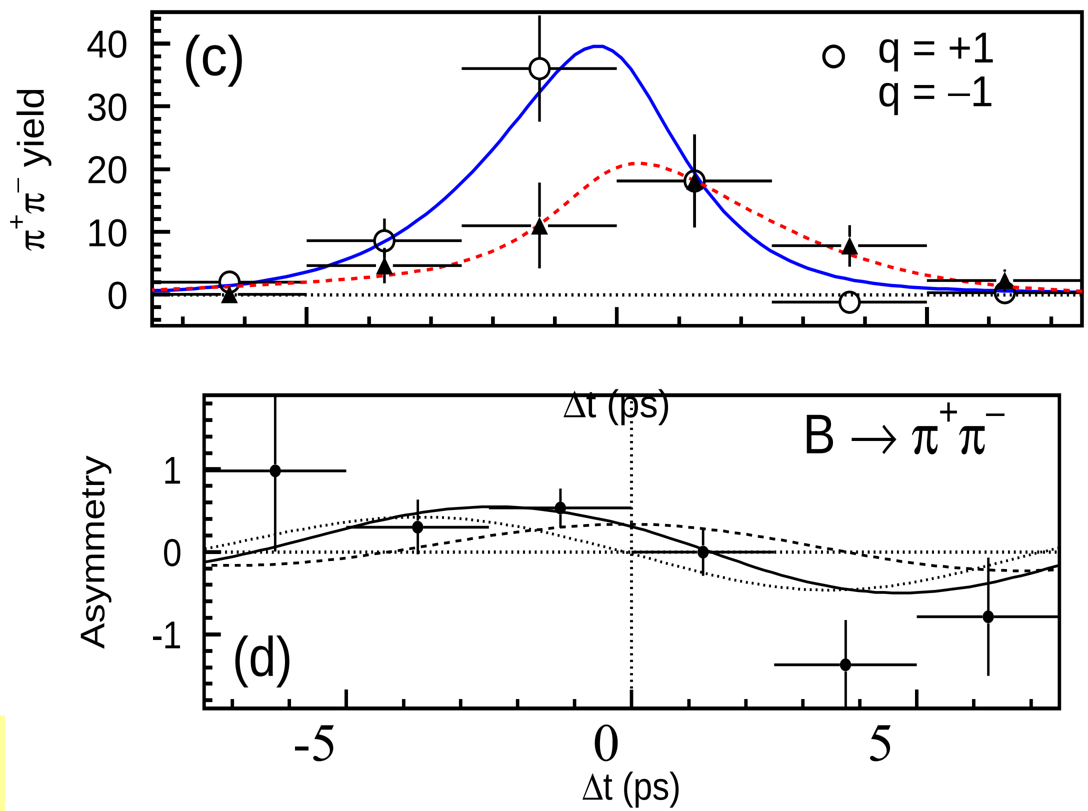
A = –0.015±0.022
S = 0.045 ±0.033

$S_{K\pi}$ = 0.08 ± 0.16
$A_{K\pi}$ =–0.03 ± 0.11
(consistent with counting analysis)

Fit Results

$$A_{\pi\pi} = +0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst})$$
$$S_{\pi\pi} = -1.23 \pm 0.41(\text{stat})\ {}^{+0.08}_{-0.07}\ (\text{syst})$$

After background subtraction



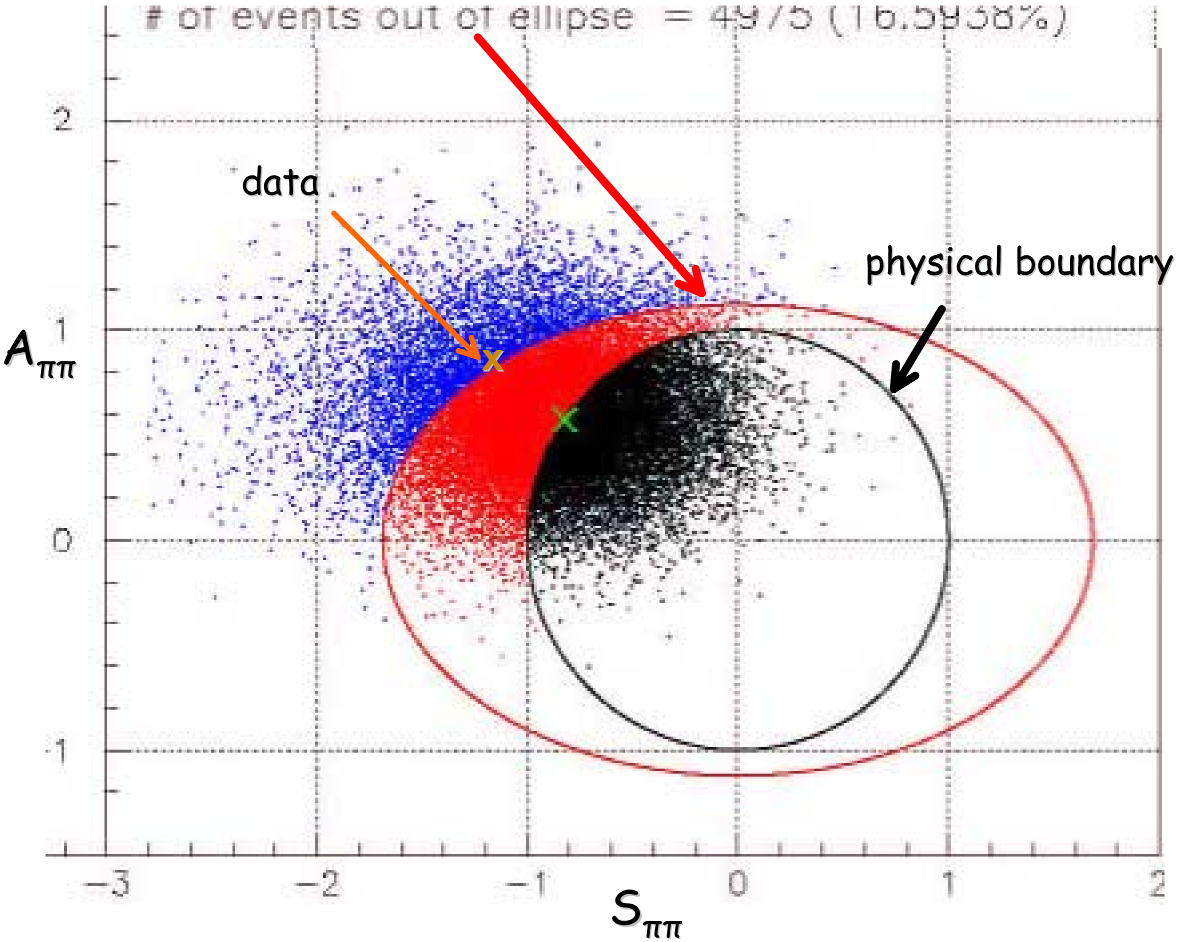
data points with LR > 0.825
curves from combined fit result

Fit Results: Statistical Issues

- MC ensemble - 30k expts, 760 events ea, $A_{\pi\pi}$=0.569, $S_{\pi\pi}$=-0.822

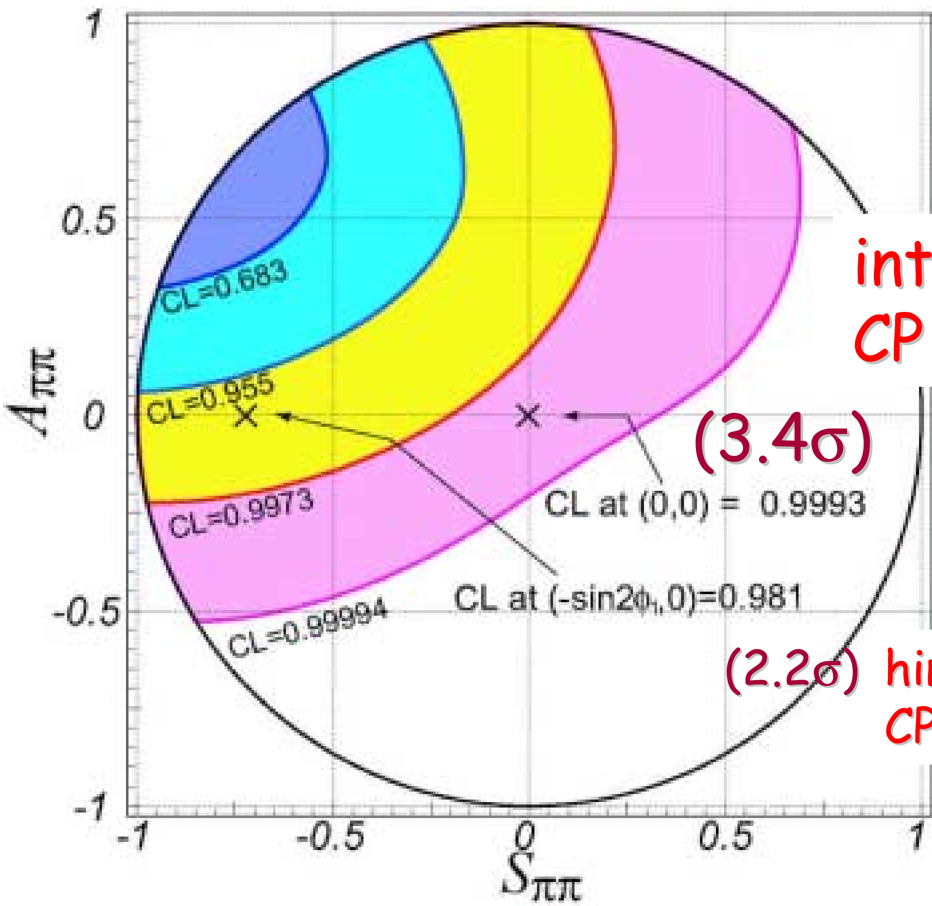
probability of being outside physical boundary =60.1%

"   further (in σ) from (0,0)=16.6%



Confidence Regions:

- Feldman-Cousins frequentist approach using Toy MC exps.
- Acceptance regions from MC ensembles.
- Systematic errors included.
- Confidence Level (CL) calculated at each point.



interpret as evidence for
CP non-conservation in $B^0 \to \pi^+\pi^-$

(3.4σ)

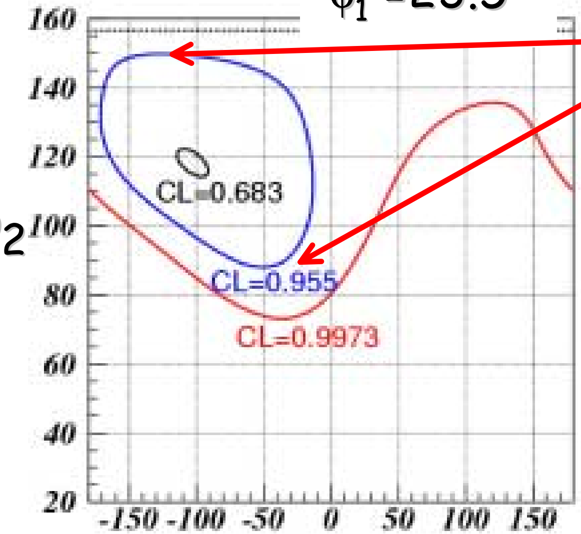
(2.2σ) hint of direct
CP violation

Constraints on the CKM angle φ_2 (α)

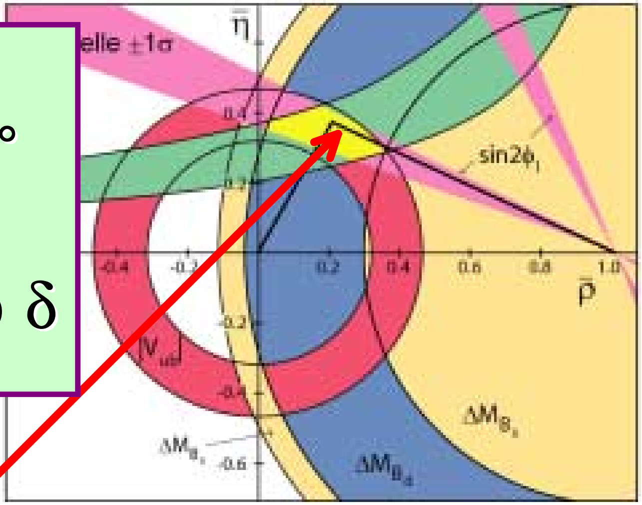
- $S_{\pi\pi}$, $A_{\pi\pi}$ depend on 4 parameters:
  ϕ_2, ϕ_1[21.3° -25.9°], |P/T|[0.15-0.45], δ
  -> plot confidence contours in (ϕ_2, δ) for various |P/T|

e.g.

|P/T|=0.3
ϕ_1 =23.5°

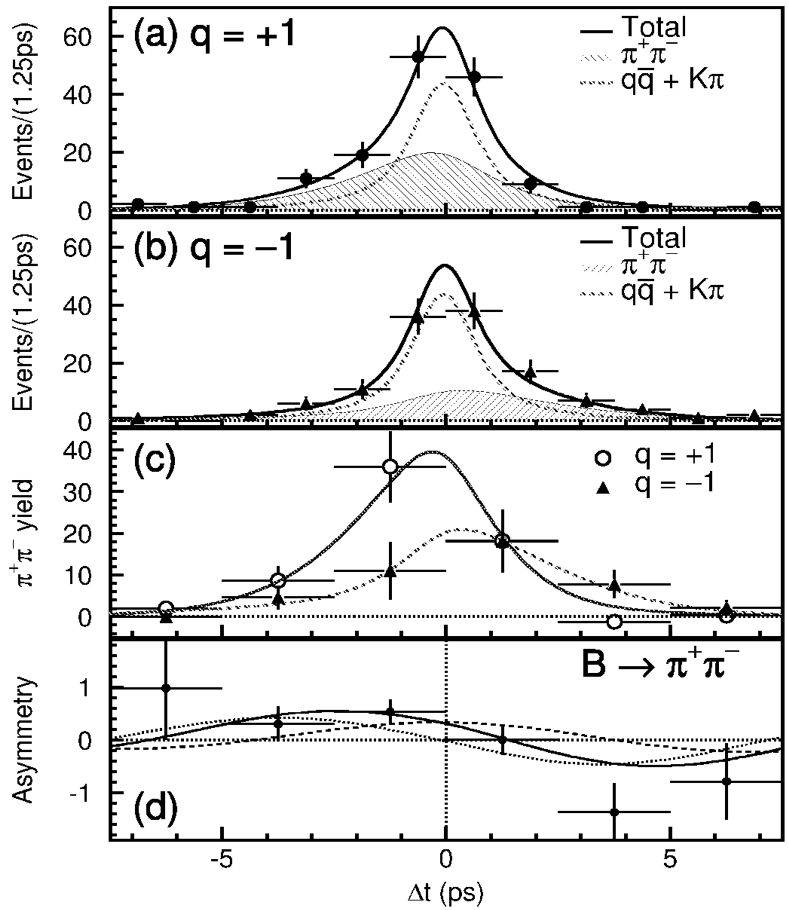


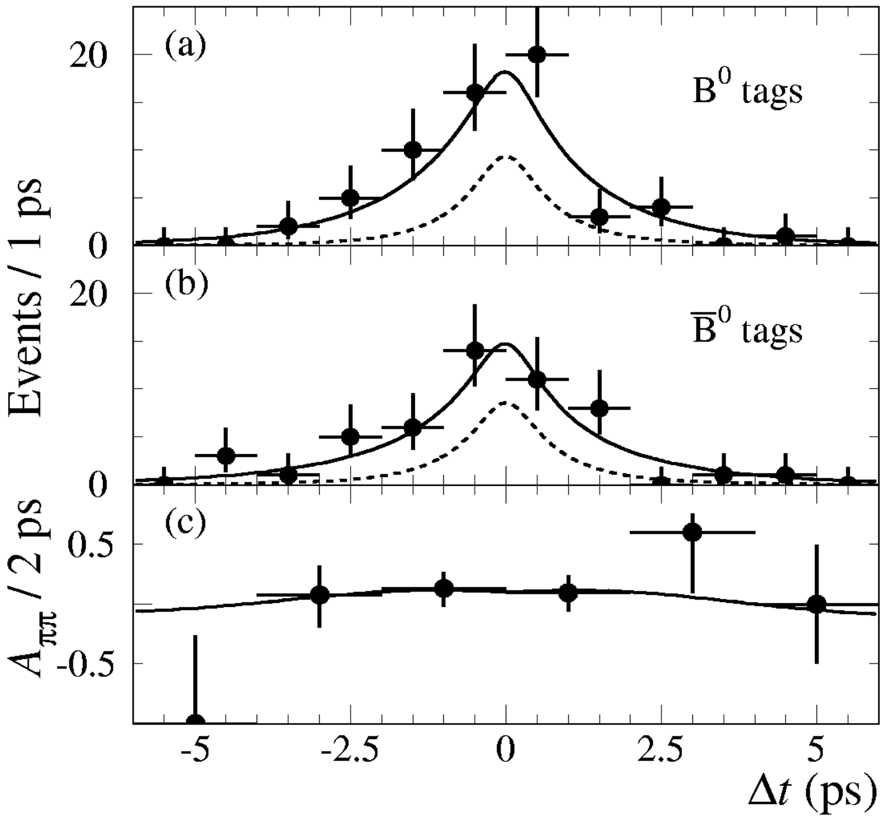
Find:
$78° \le \phi_2 \le 152°$
(95% C.L.)
insensitive to δ



Indirect constraints (CKM fitter group):
$78.3° \le \phi_2 \le 121.6°$ (95% C.L.)
➔ consistent

Data: Belle (78 fb^{-1}) versus Babar (81 fb^{-1})

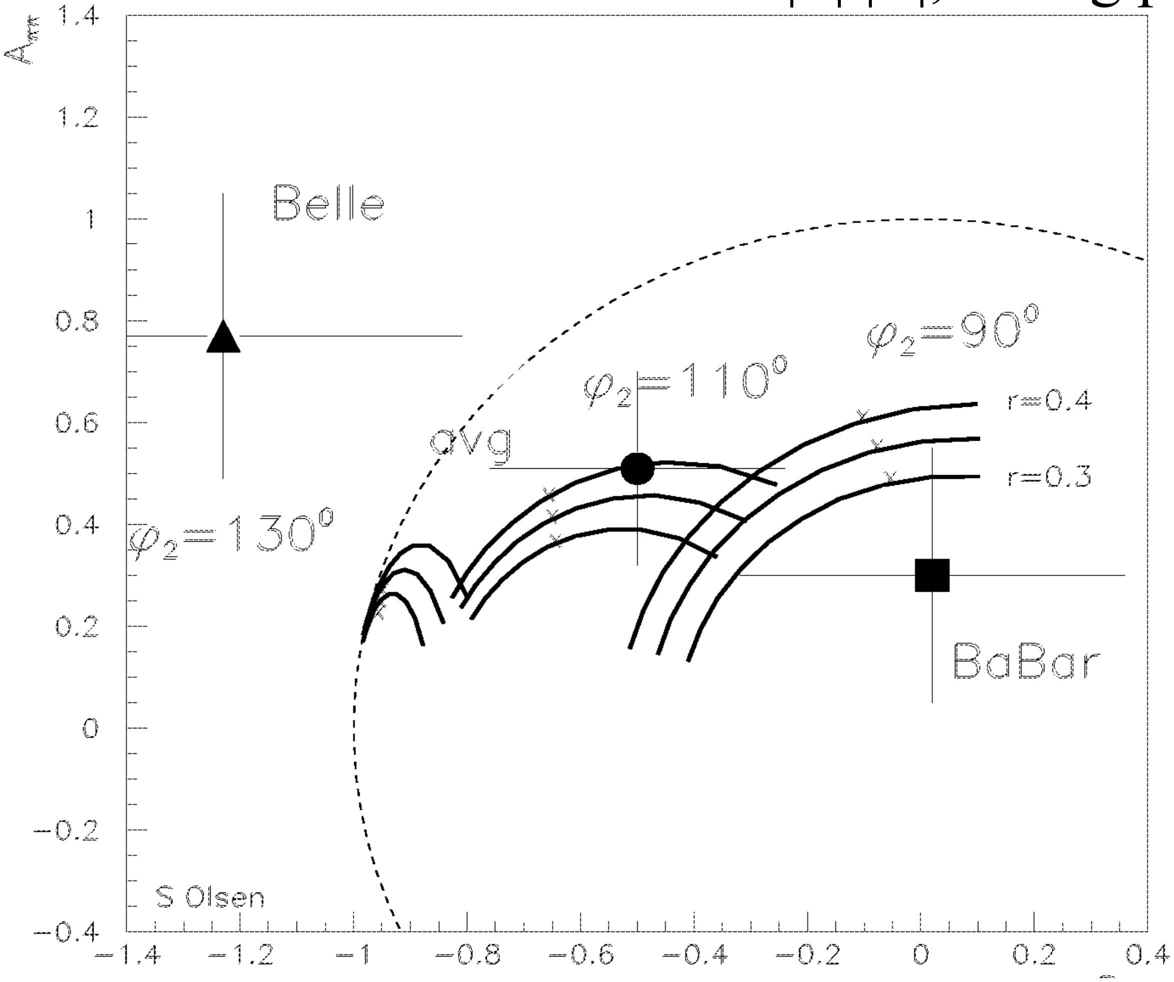




Comparison of Belle and BaBar ($S_{\pi\pi}$,$A_{\pi\pi}$)

r=|P|/|T|; strong phase difference

$A_{\pi\pi}$



$S_{\pi\pi}$

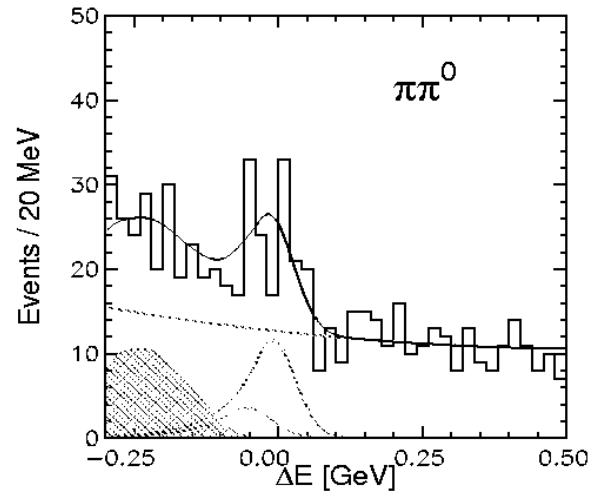
Branching Fraction Results for B→h h Modes

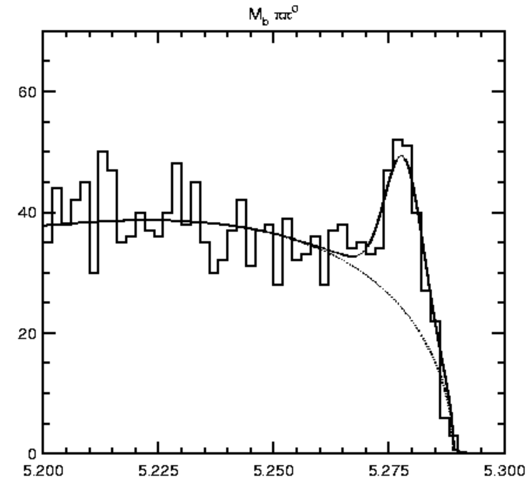
29 fb^{-1} (PRD 66, 092002 2002, B.C.K Casey et al)→78 fb^{-1}

Mode	N_s	$\mathcal{S}$ [σ]	ϵ [%]	$\mathcal{B}[10^{-6}]$
$K^+\pi^-$	$595.9^{+33.2}_{-32.5}$	24.1	37.9	$18.5 \pm 1.0 \pm 0.7$
$K^+\pi^0$	198.9 ± 21.5	10.8	18.3	$12.8 \pm 1.4 ^{+1.4}_{-1.0}$
$K^0\pi^+$	187.0 ± 16.3	16.4	10.0	$22.0 \pm 1.9 \pm 1.1$
$K^0\pi^0$	72.6 ± 14.0	5.8	6.8	$12.6 \pm 2.4 \pm 1.4$
$\pi^+\pi^-$	$132.7^{+18.9}_{-18.2}$	8.5	35.2	$4.4 \pm 0.6 \pm 0.3$
$\pi^+\pi^0$	72.4 ± 17.4	4.5	16.1	$5.3 \pm 1.3 \pm 0.5$
$\pi^0\pi^0$	$12.0^{+9.1}_{-8.6}$	1.9	7.8	$1.8^{+1.4}_{-1.3}{}^{+0.5}_{-0.7} < 4.4$
K^+K^-	$-1.0^{+6.6}_{-5.9}$	0.0	20.1	< 0.7
$K^+\overline{K}^0$	8.6 ± 5.9	1.6	5.9	$1.7 \pm 1.2 \pm 0.1 < 3.4$
$K^0\overline{K}^0$	2.0 ± 1.9	1.3	2.9	$0.8 \pm 0.8 \pm 0.1 < 3.2$

These measurements provide additional clues.

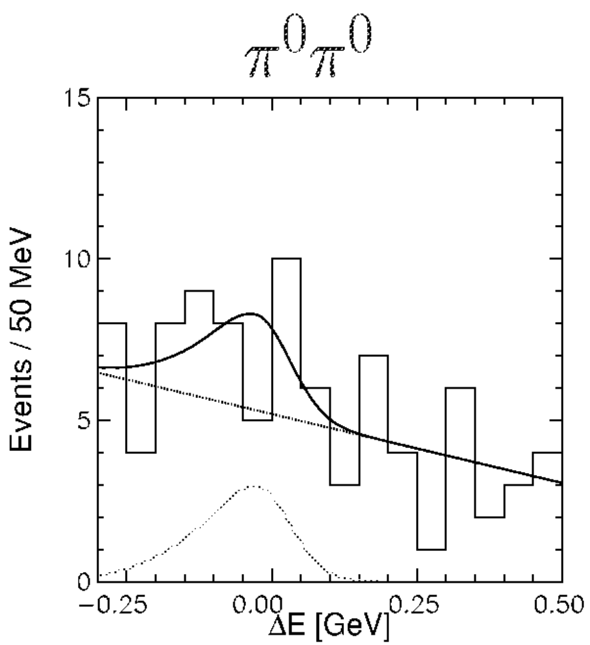
Data for $B^+ \to \pi^+ \pi^0$ and $B \to \pi^0 \pi^0$





72.4±17.4

(4.5σ)

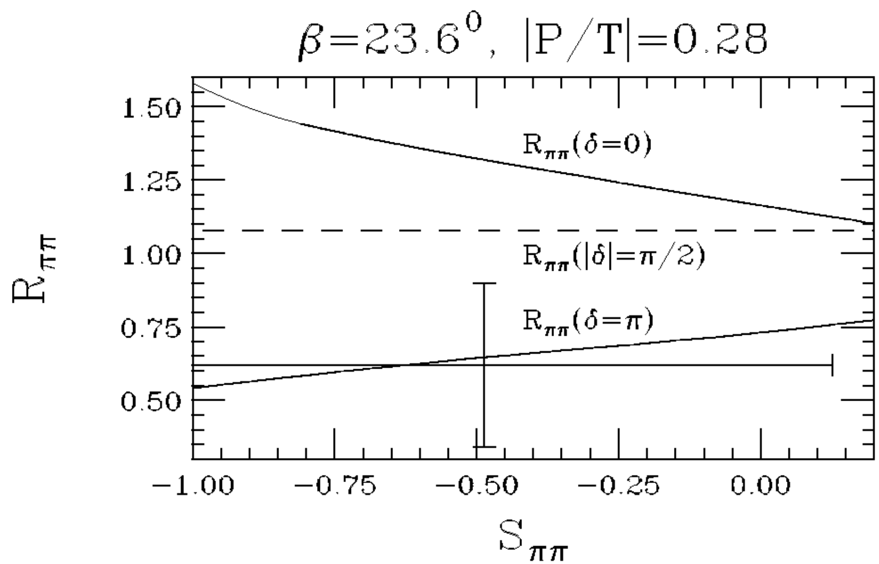


N=12.0$\pm^{9.1}_{8.6}$ (1.9σ)

Clues from the Ratios of Branching Fractions

Modes	Ratio @78 fb^{-1}
$\Gamma(\pi^+\pi^-)\ /\ \Gamma(K^+\pi^-)$	$0.24 \pm 0.04 \pm 0.02$
$2\Gamma(K^+\pi^0)/\ \Gamma(K^0\pi^+)$	$1.16 \pm 0.16\ ^{+\ 0.14}_{-\ 0.11}$
$\Gamma(K^+\pi^-)/\ \Gamma(K^0\pi^+)$	$0.91 \pm 0.09 \pm 0.06$
$\Gamma(K^+\pi^-)/2\Gamma(K^0\pi^0)$	$0.74 \pm 0.15 \pm 0.09$
$\Gamma(\pi^+\pi^-)\ /2\Gamma(\pi^+\pi^0)$	$0.45 \pm 0.13 \pm 0.05$
$\Gamma(\pi^0\pi^0)\ \ /\ \Gamma(\pi^+\pi^0)$	< 0.92

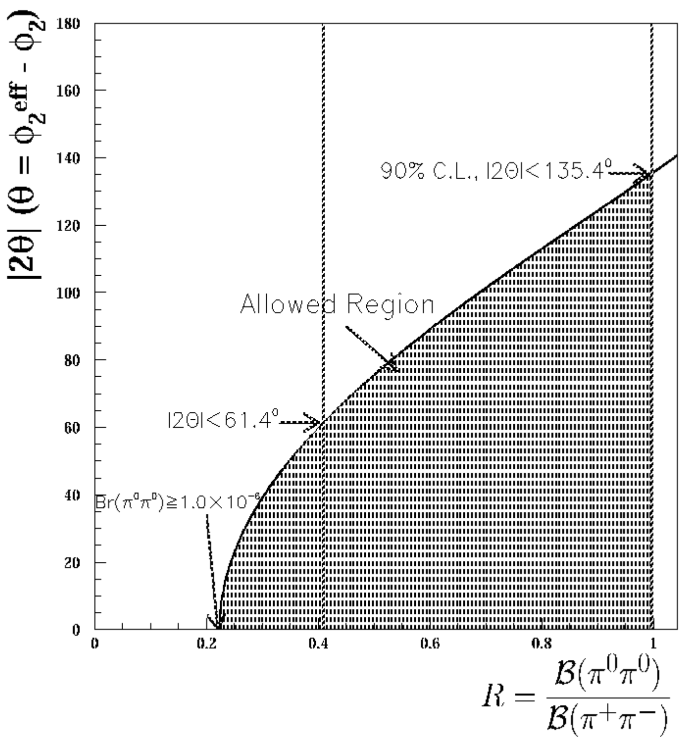
The deviation of $\Gamma(\pi^+ \pi^-)/2\,\Gamma(\pi^+ \pi^0)$ from unity indicates: either $\varphi_3 > 90^0$ or large FSI or a large color suppressed contribution.



Rosner, hep-ph/0304200

The bound $\Gamma(\pi^0\pi^0)/ 2\Gamma(\pi^+\pi^0)$ gives a weak limit on $\theta= |\varphi_{2eff} - \varphi_2| < 68^0$ (e.g. Grossman-Quinn bound)

2 θ



$B(\pi^0\pi^0)/ B(\pi^+\pi^0)$

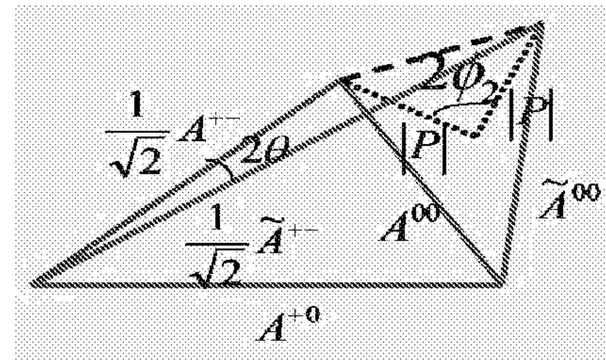


FIG. 10. The A and $\tilde{A}$ isospin triangles.

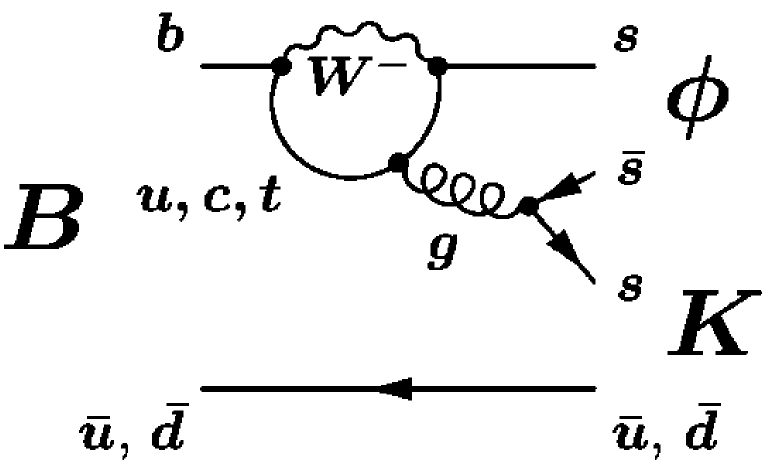
M. Gronau and D.London.

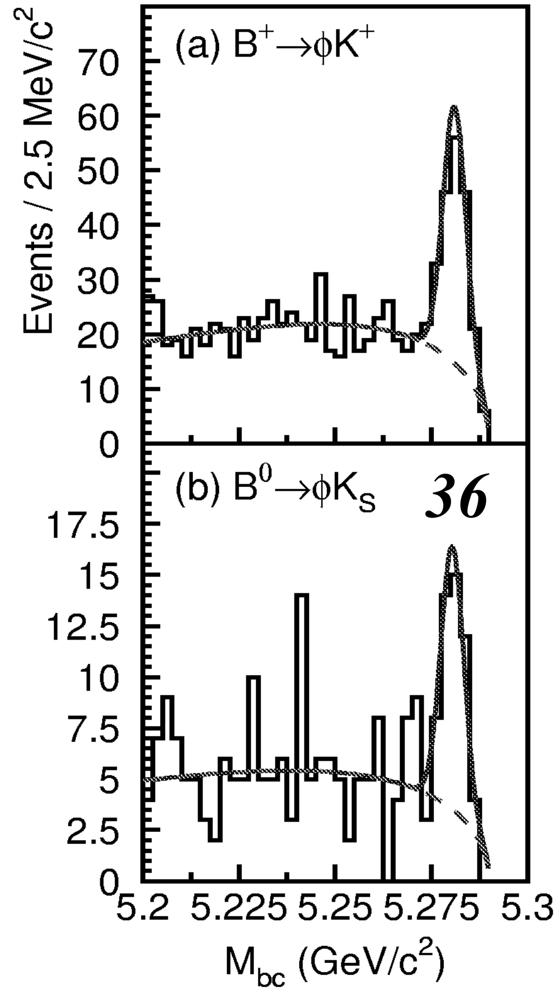
PRL 65, 2381 (90)

Dreams of New Physics and Adventures with rare B decays.

Hunting for phases from new physics

Example:

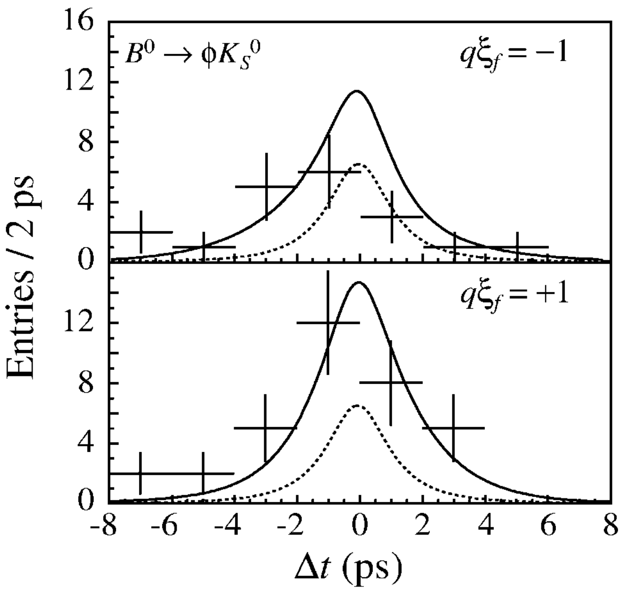


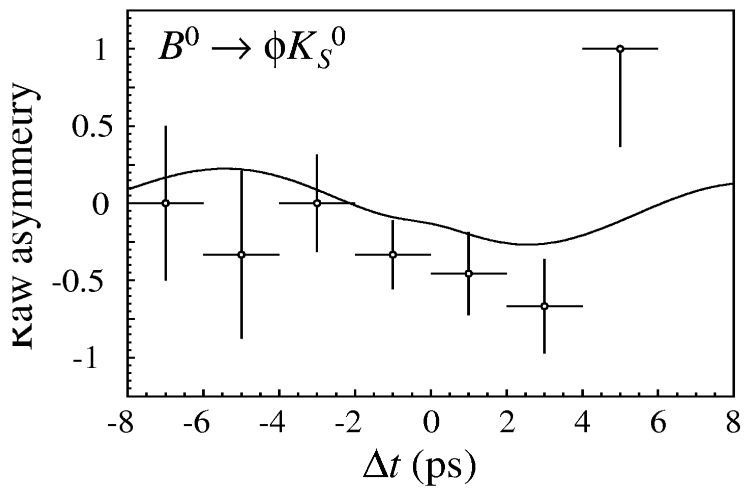


36

In the SM, $\sin(2\varphi_1)^{\mathrm{eff}} = \sin(2\varphi_1)$ ($B \rightarrow \psi K_S$)

Hunting for new phases in b→s penguins





(hep-ph/0209290), J-P Lee, K. Y. Lee; (hep-ph/0208226) B. Dutta, C.S. Kim and S. Oh; (hep-ph/0208091), M. Raidal; (hep-ph/0208087), M. Ciuchini, L. Silvestrini; (hep-ph/0208016), A. Datta;(hep-ph/0208005), H. Murayama;(hep-ph/0207356), G. Hiller; (hep-ph/0207070), M-B. Causse; (hep-ph/0208080) Y. Nir ….

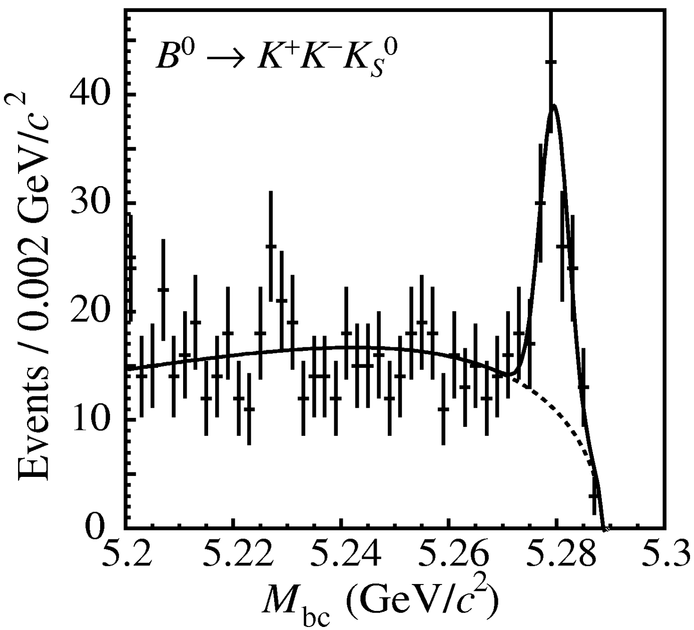
K. Abe et al,PRD 67, 03402(R),2003

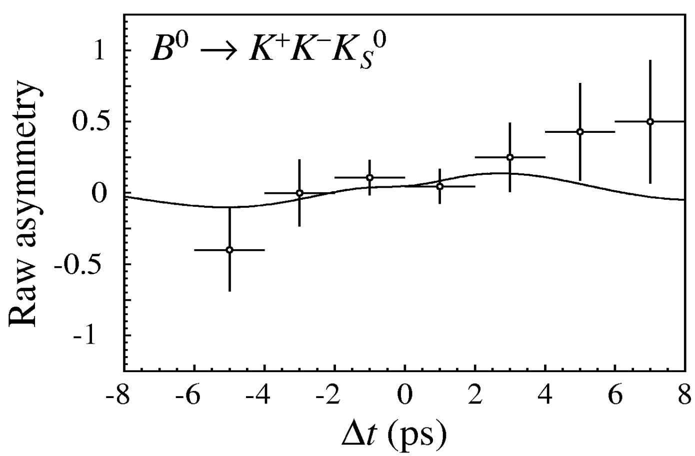
→ Belle: $\sin2\varphi_{1eff}$ = -0.73 ±0.64 ±0.22

c.f. Babar: $\sin2\varphi_{1eff}$ = -0.19±0.51 ±0.09

2.7σ off *WA: $\sin2\varphi_{1eff}(\varphi K_S)$ = -0.39 ±0.41*

N(K K K_S)=96±10





Search for New Physics in the $B \to K^+ K^- K_S$ penguin decay.

$$S_{KKKs} = 0.49 \pm 0.43 \pm 0.11 {}^{+0.33}_{-0.00}$$

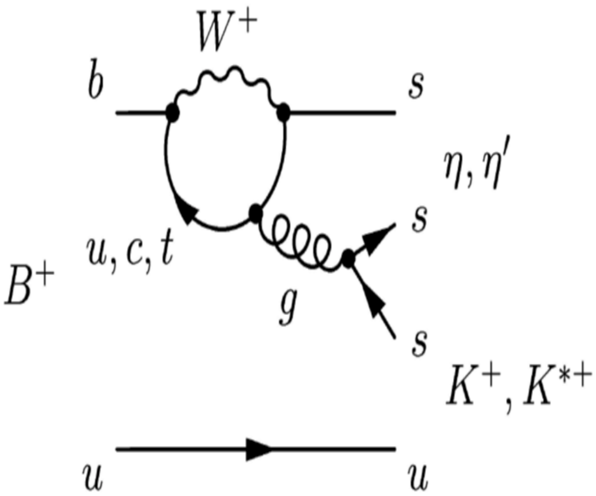
The third error is due to uncertainty in the CP content.

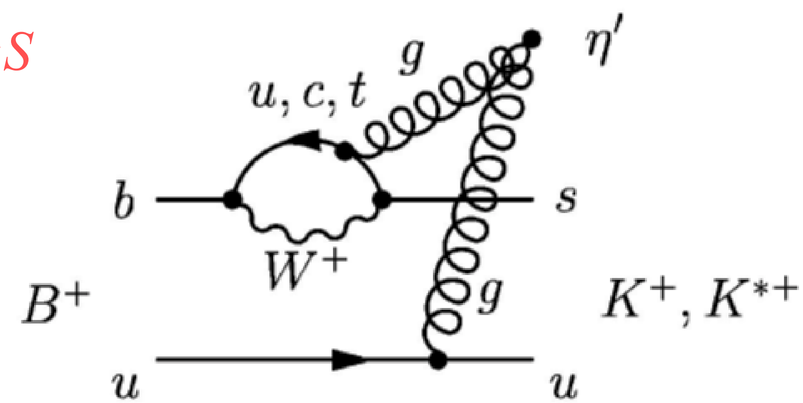
In the absence of New Physics, $S_{KKKs} = \sin(2\varphi_1)$

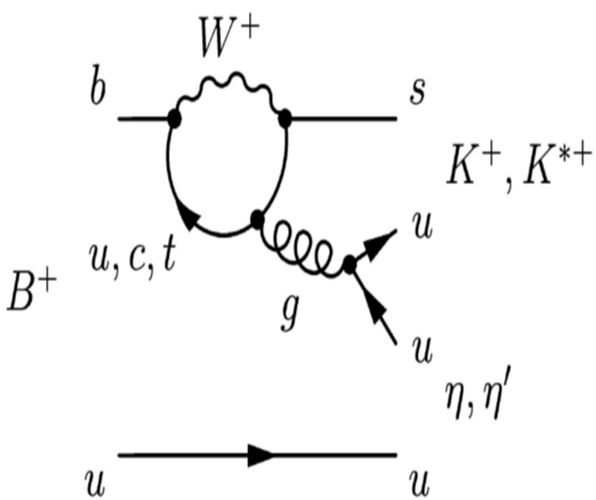
Current WA: $\sin(2\varphi_1) = 0.734 \pm 0.055$

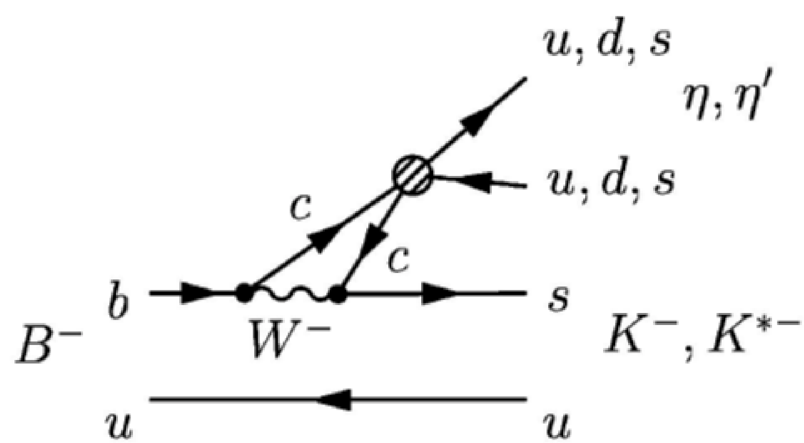
Hunting for new phases in b→s penguins

$B \rightarrow \eta' K_S$



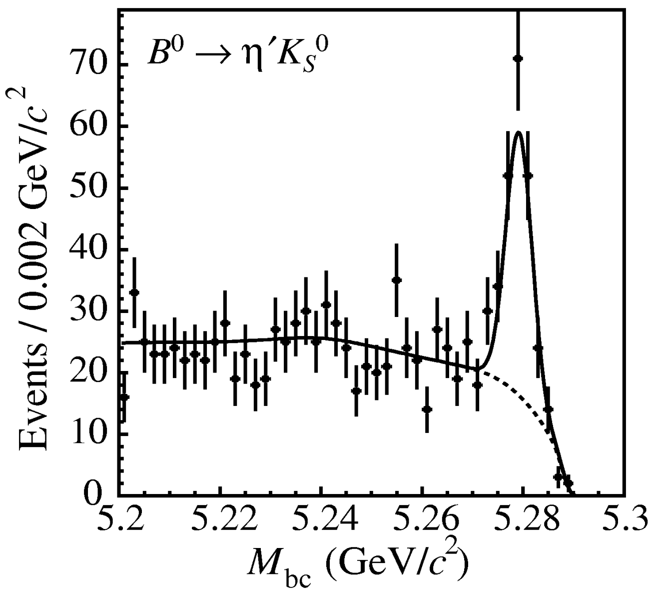


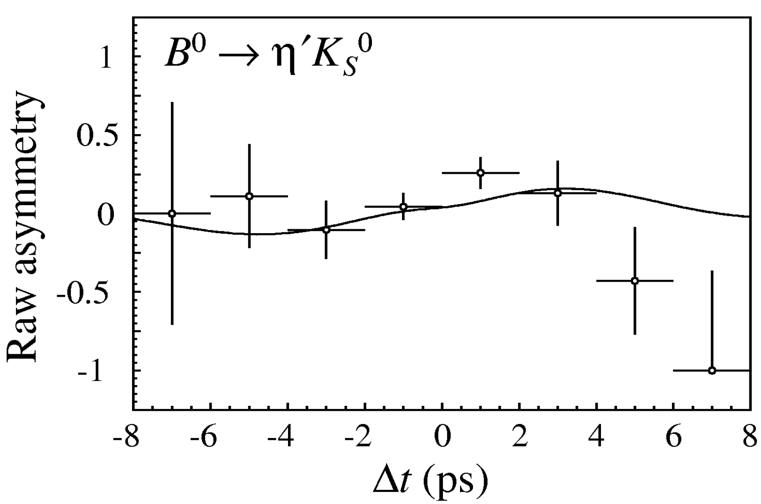




Large rates for exclusive and inclusive $B \rightarrow \eta' X_s$ decays.

$N(\eta' K_S)=146\pm12$





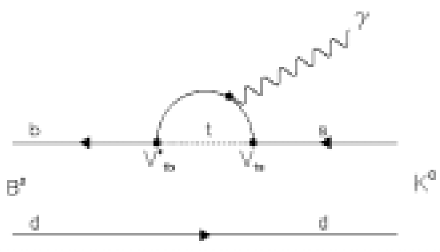
Search for New Physics in the B→ η'K$_S$ penguin decay.

$$S_{\eta' K_s} = 0.71\pm0.37 {}^{+0.05}_{-0.06}$$

In the absence of New Physics, $S_{\eta' K_s} = \sin(2\varphi_1)$ (a.k.a. $\sin(2\beta)$)

Current WA: $\sin(2\varphi_1)=0.734\pm0.055$

The Hunt for the EW Penguin: $B \rightarrow X_s\, l^+ l^-$



Discovered by CLEO in 1994

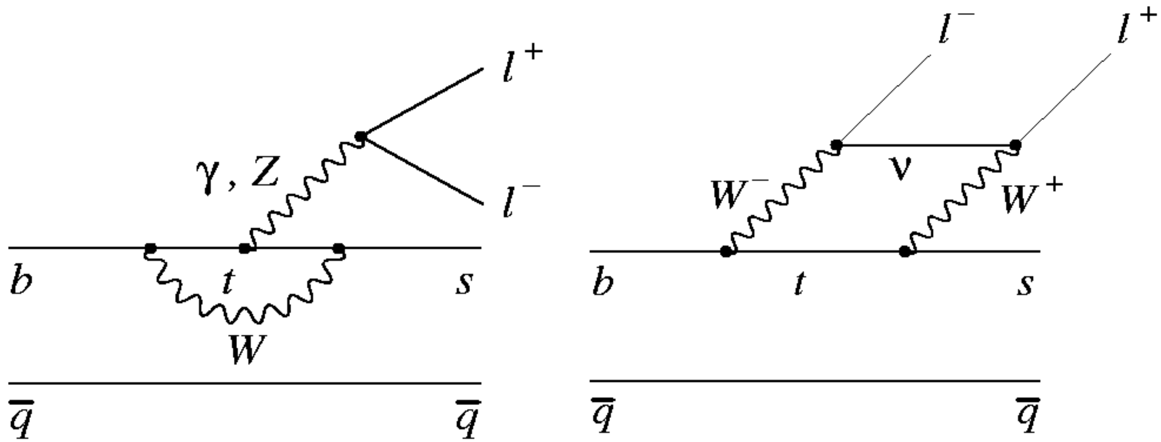
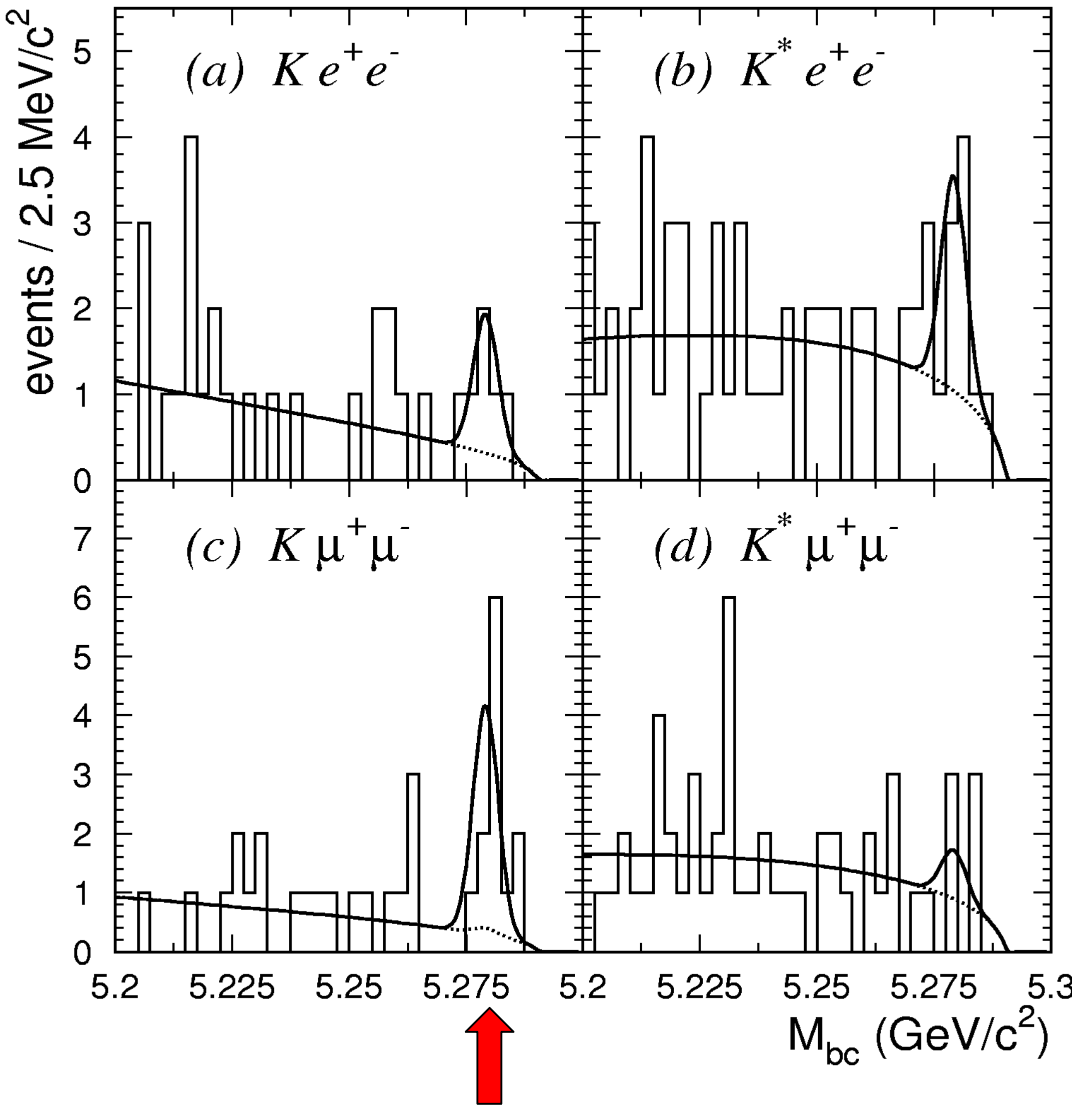


Figure 1: Standard Model diagrams for the decays $B \rightarrow K^{(*)}\ell^+\ell^-$.

As in $b \rightarrow s\, \gamma$, heavy particles in the loops can be replaced with NP particles (e.g. $W^+ \rightarrow H^+$)

Note contributions from virtual γ^*, W, Z^* and internal t quark.

Belle 2001: Observation of B→K $l^+ l^-$



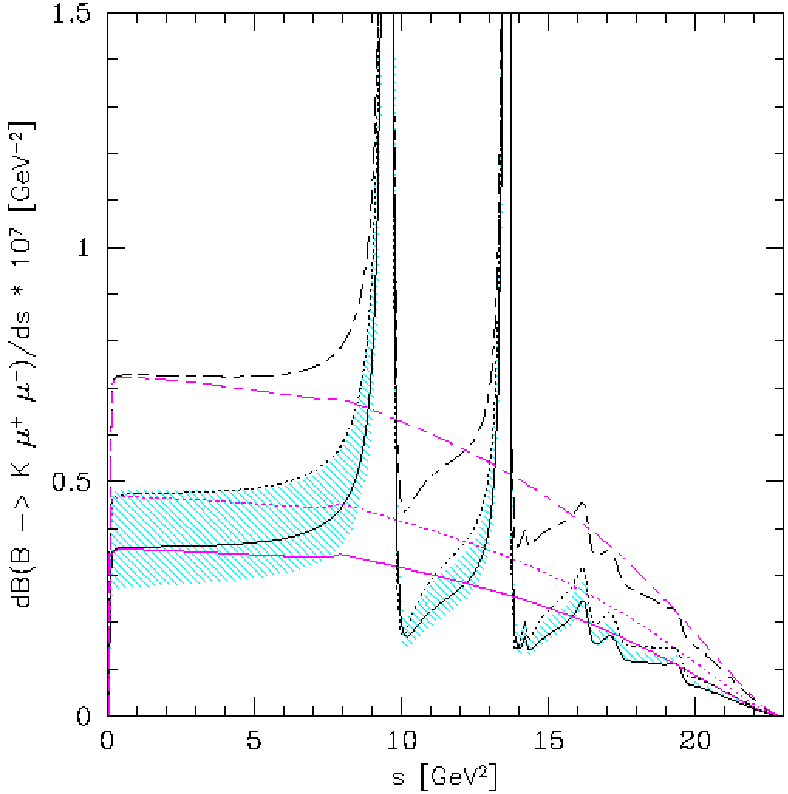
$$BF = (0.75 ^{+0.25}_{-0.21} \pm 0.09) \times 10^{-6}$$

PRL 88, 052002 (2002)

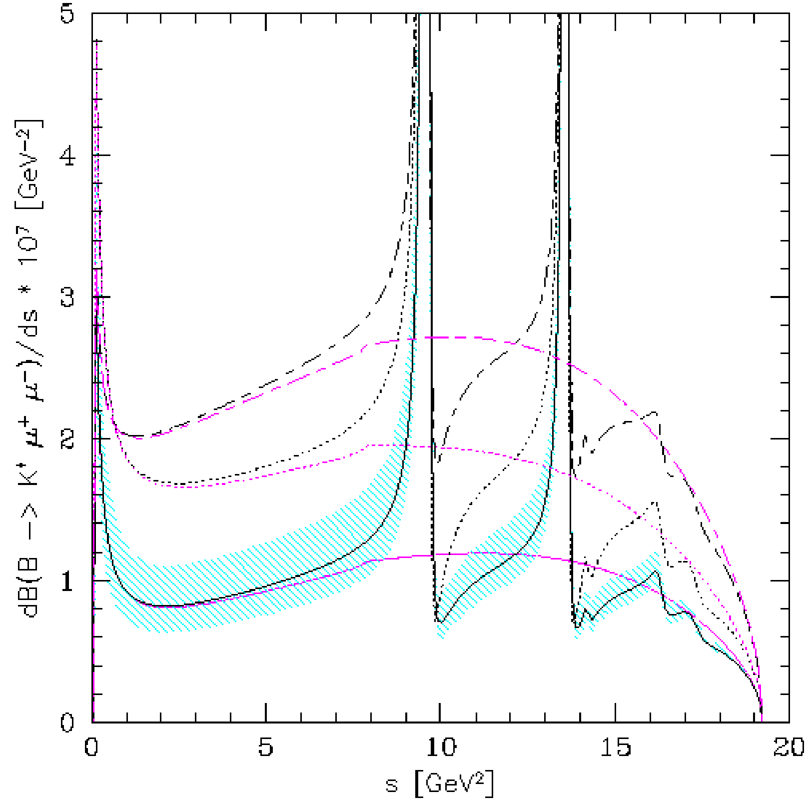
Recently confirmed by BaBar (preliminary)

Predicted distributions for $q^2 = M^2_{l+l-}$

$B \to K\,\mu^+\mu^-$:



$B \to K^{*0}\,\mu^+\mu^-$ (pole at $q^2 = 0$):



- Solid line + blue bands: SM range (± 35%); Ali et al. form factors
- Dotted line: SUGRA model (R_7 = -1.2, R_9 = 1.03, R_{10} = 1)
- Long-short dashed line: SUSY model (R_7 = -0.83, R_9 = 0.92, R_{10} = 1.61)

m_{l+l-} distributions for B→K l^+ l^-

Belle 2002 (update)

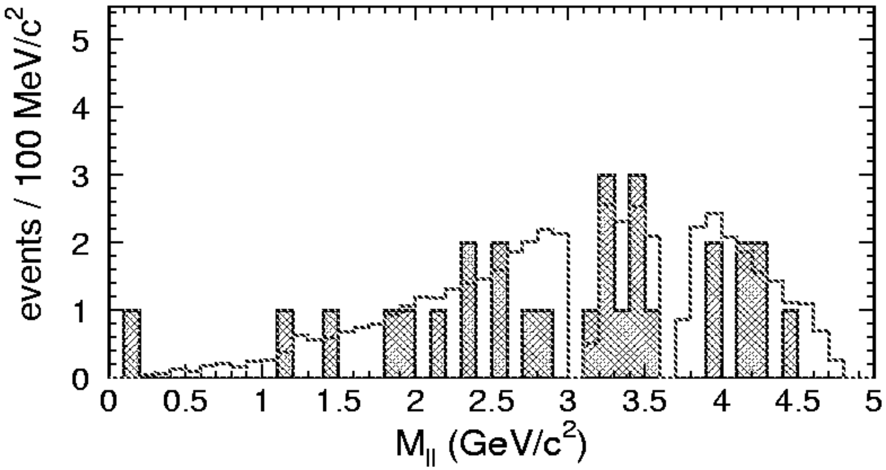


FIG. 5. The dilepton mass distributions for $B \to K\ell^+\ell^-$ candidates. The hatched histogram shows the data distribution while the open histogram shows the MC signal distribution.

Consistent with the SM. Statistics are low

Theoretical predictions: exclusive b→s $l^+ l^-$ modes

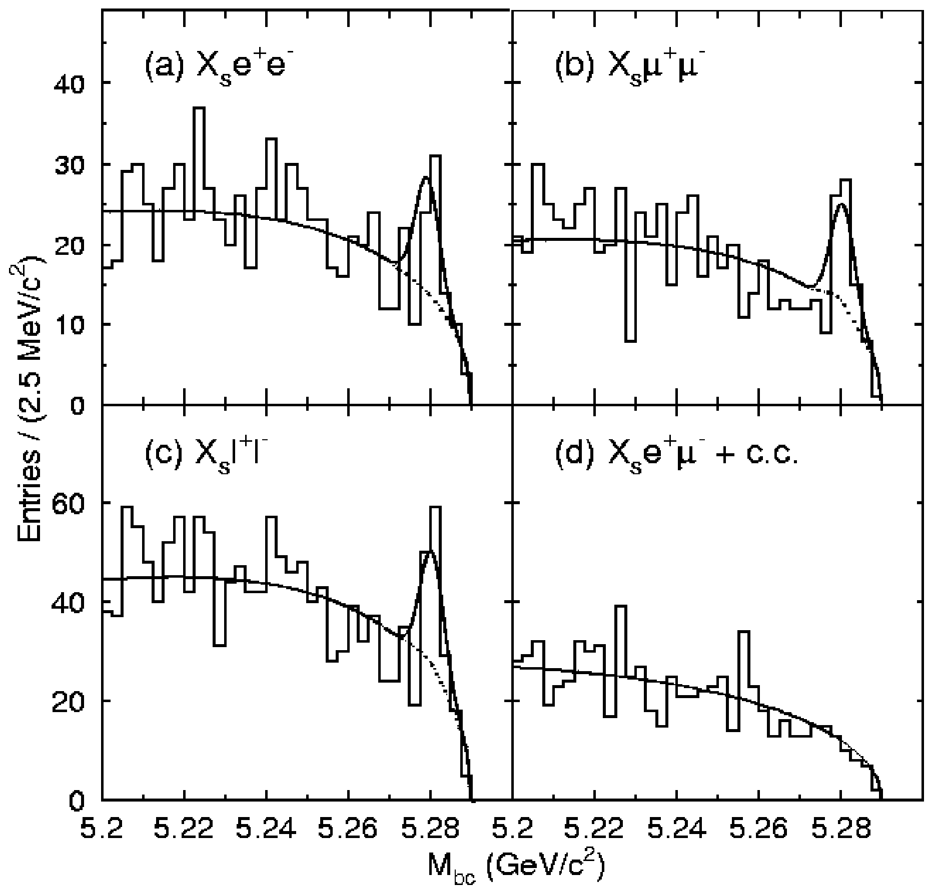
Authors	$\mathcal{B}(B\to K l^+ l^-)$ $/10^{-6}$	$\mathcal{B}(B\to K^* \mu^+ \mu^-)$ $/10^{-6}$	$\mathcal{B}(B\to K^* e^+ e^-)$ $/10^{-6}$
Ali *et al.* (2000) →	$0.57^{+0.17}_{-0.10}$	$1.9^{+0.5}_{-0.4}$ ↔	$2.3^{+0.7}_{-0.5}$
Ali *et al.* (2001) [NNLO] →	0.35 ± 0.12	1.19 ± 0.39	1.58 ± 0.49
Aliev *et al.* (1997)	0.31 ± 0.09	1.4	
Colangelo *et al.* (1996)	0.3	1.0	
Faessler *et al.* (2002)	0.55	0.81	
Geng and Kao (1996)	0.5	1.4	
Melikhov *et al.* (1998)	0.44	1.15	1.50
Zhong *et al.* (2002)	$0.69^{+0.28}_{-0.25}$	$1.98^{+0.66}_{-0.71}$	$2.01^{+0.65}_{-0.73}$

- $\mathcal{B}(B\to K\ell^+\ell^-) =$ ← **dominant uncertainty: form factors**
  $(0.35 \pm 0.11(\text{form fac.}) \pm 0.04(\mu_b) \pm 0.02(m_{t,\text{pole}}) \pm 0.0005(m_c/m_b)) \times 10^{-6}$
  [Ali, Lunghi, Greub, Hiller, hep-ph/0112300, 2001]

New calculations of QCD corrections predict too high a rate for B->K*γ; the necessary adjustment of T_1 form factor lowers the prediction for $B\text{->}K^*l^+l^-$.

Belle 2002: Observation of *inclusive* $B \to X_s l^+ l^-$

25.5±11.2

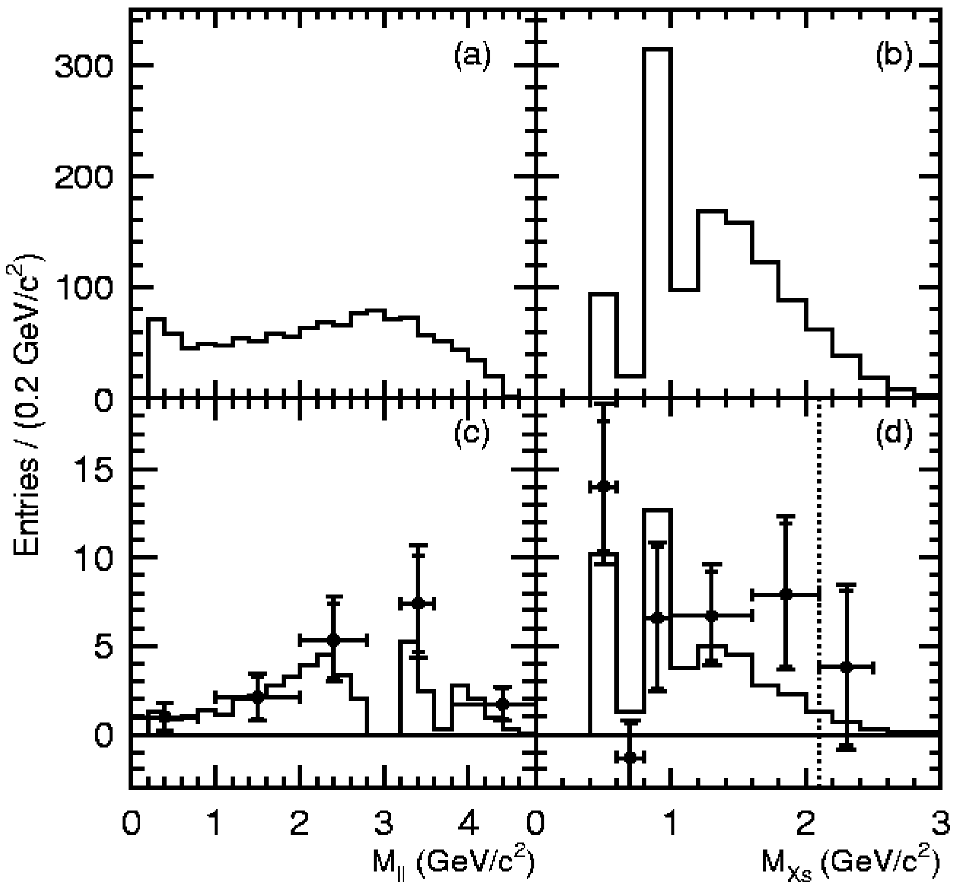


37.3±9.7

Control sample

$$BF(B \to X_s l^+ l^-) = (6.1 \pm 1.4^{+1.3}_{-1.1}) \times 10^{-6}$$

Belle 2002: M_{ll} and M_{Xs} distributions for $B \rightarrow X_s l^+ l^-$

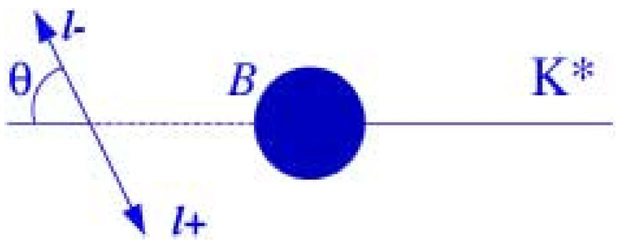


MC generator

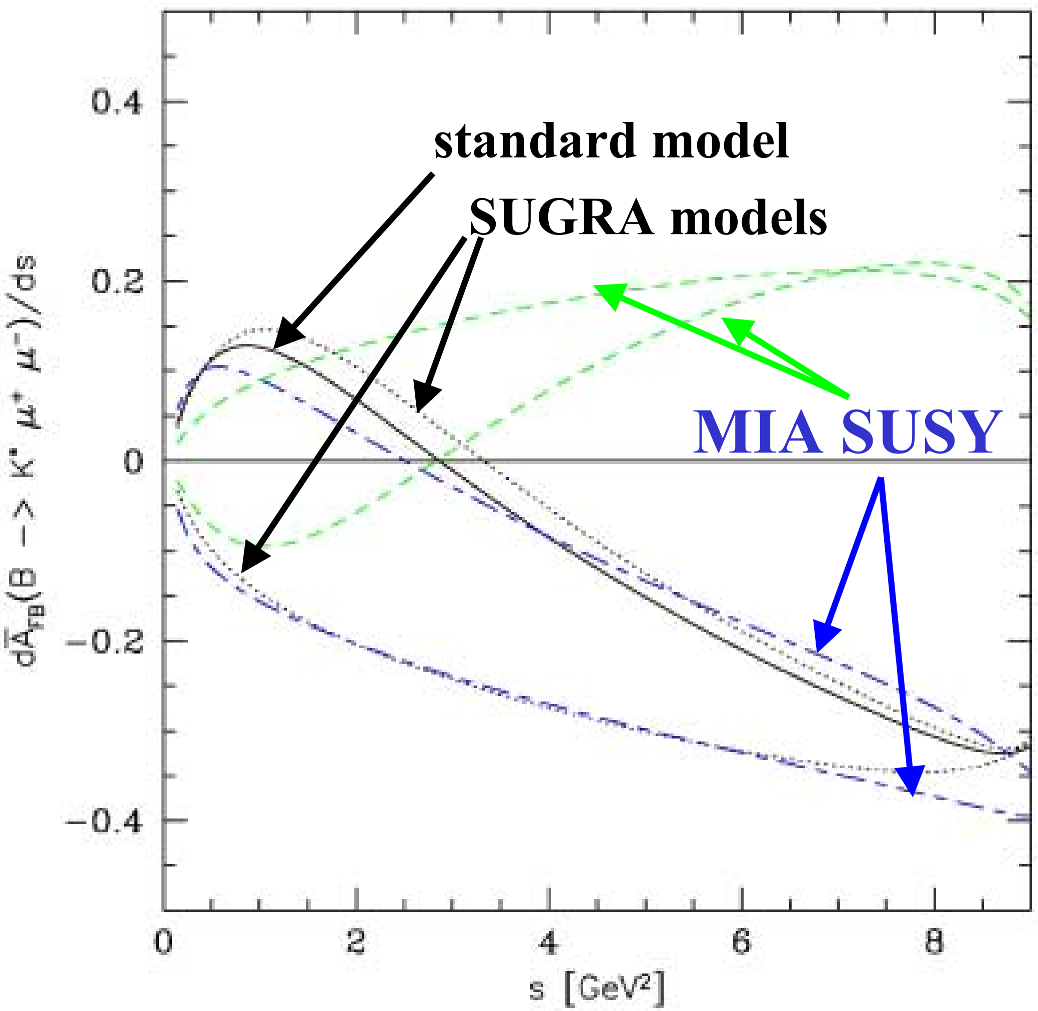
Data vs MC

hep-ex/0208029, PRL xxxx

Sensitivity to new physics in A_{FB} ($B \rightarrow K^* l^+ l^-$)



Polar angle of lepton in dilepton rest frame.



A. Ali *et al.*, PRD 61, 074024 (2000).

q^2 (GeV^2)

Super KEKB, PEP-II, L=$10^{35\text{-}36}$/cm^2/sec;

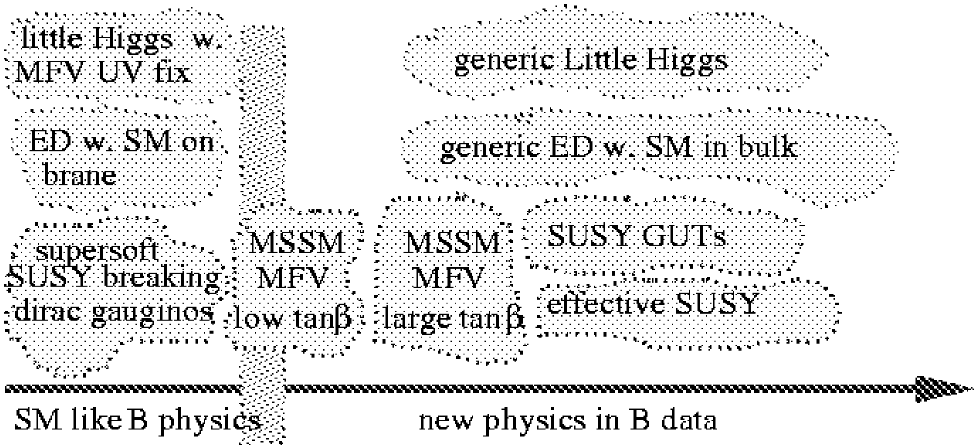


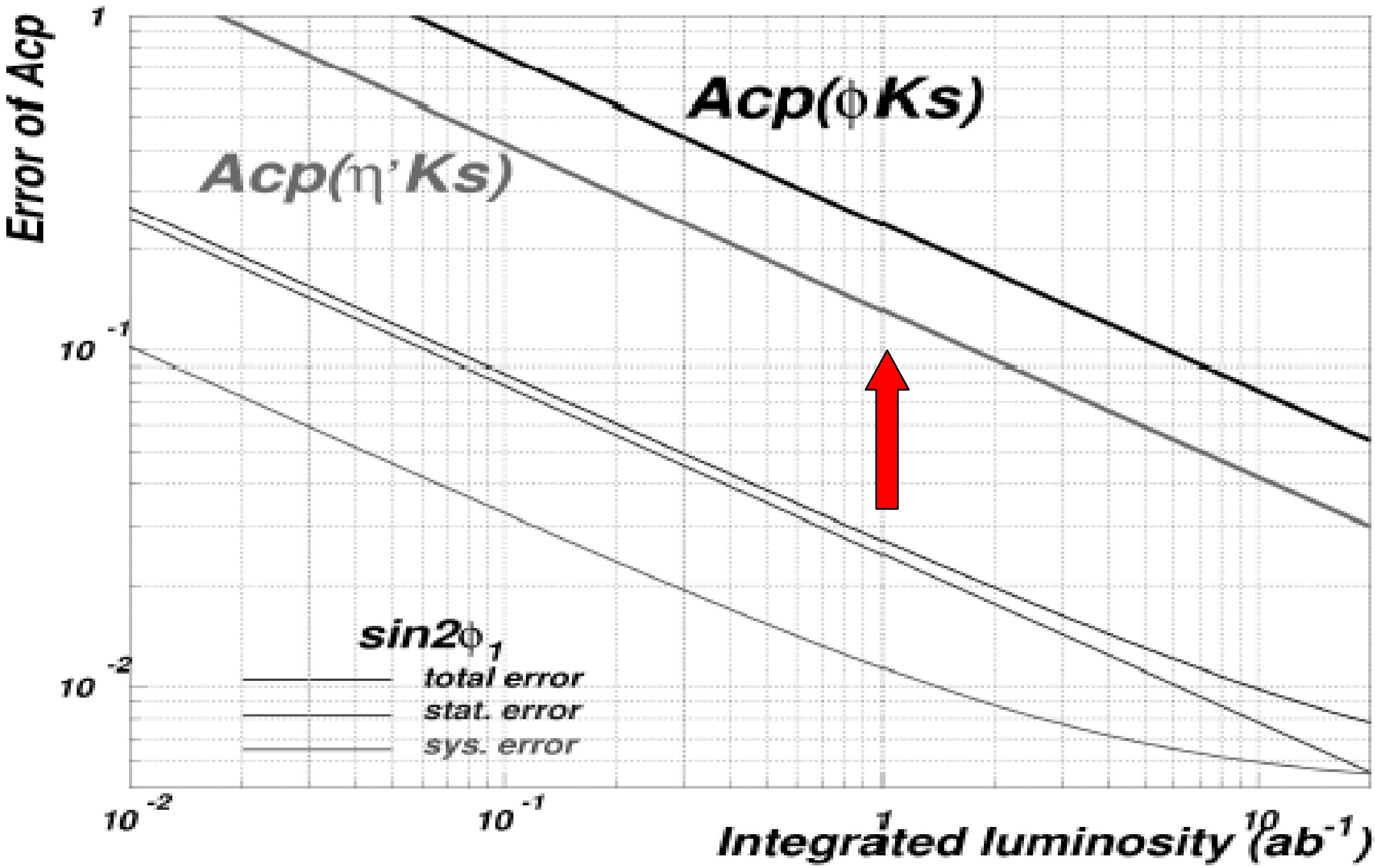
Figure 4. Flavor/CP yield of models of electroweak symmetry breaking.

G. Hiller

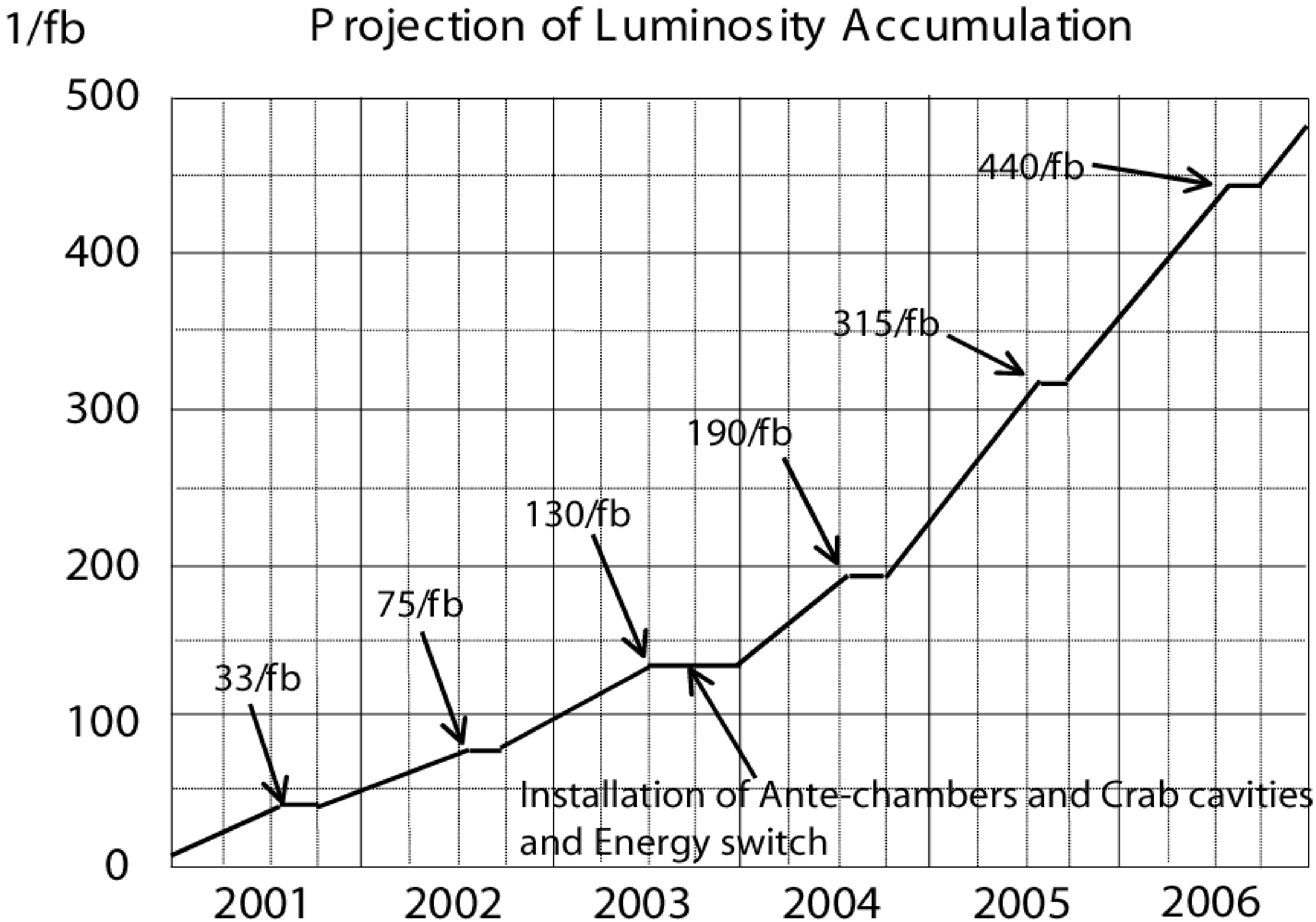
Scenarios for flavor physics beyond the SM.

Signatures in time-dependent CPV (φK_S), rare decays (e.g. $b \rightarrow s\, l^+ l^-$, $b \rightarrow s\, \gamma$)

Sensitivity to new physics phases



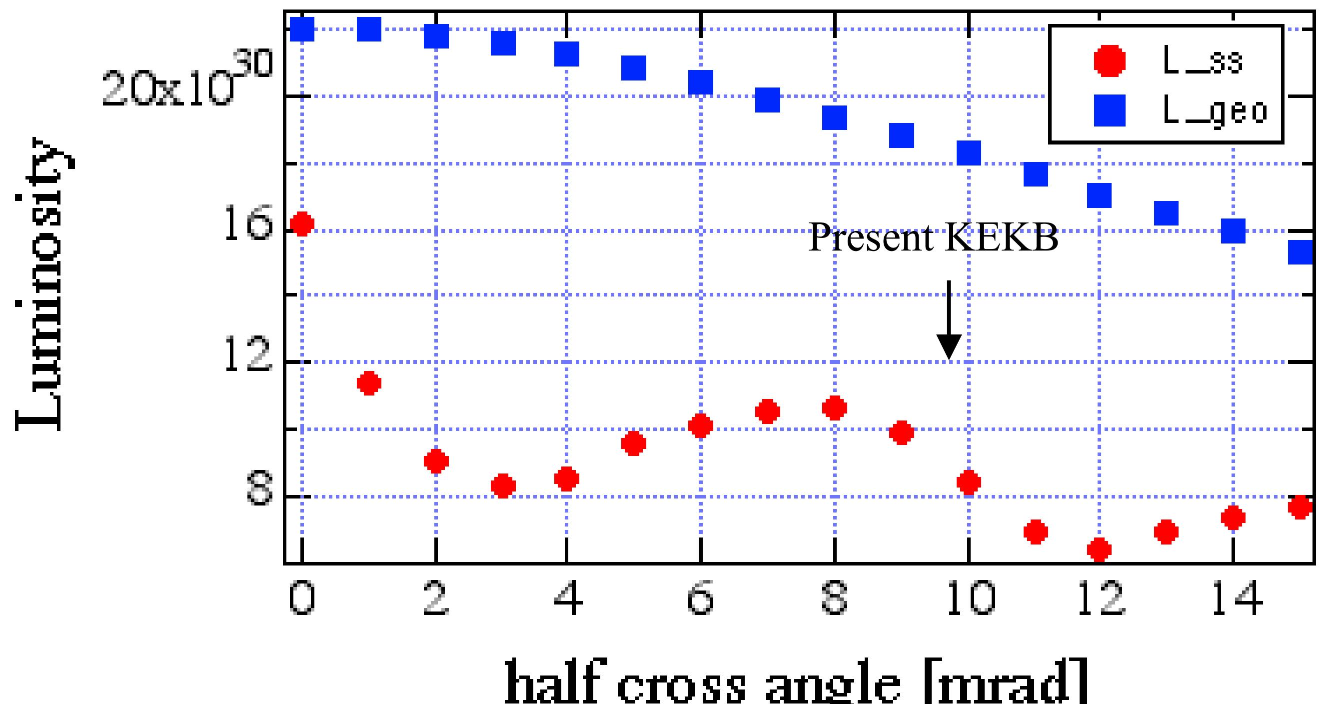
Pessimistic KEKB Future Scenario: K. Oide



Effect of crab cavity system

- Beam-Beam simulation using Ohmi's code (Tawada)
  - Luminosity will be doubled with the present machine parameters, if the crossing angle becomes zero.
    -> $\xi_y^* \sim 0.1$

(Per bunch)



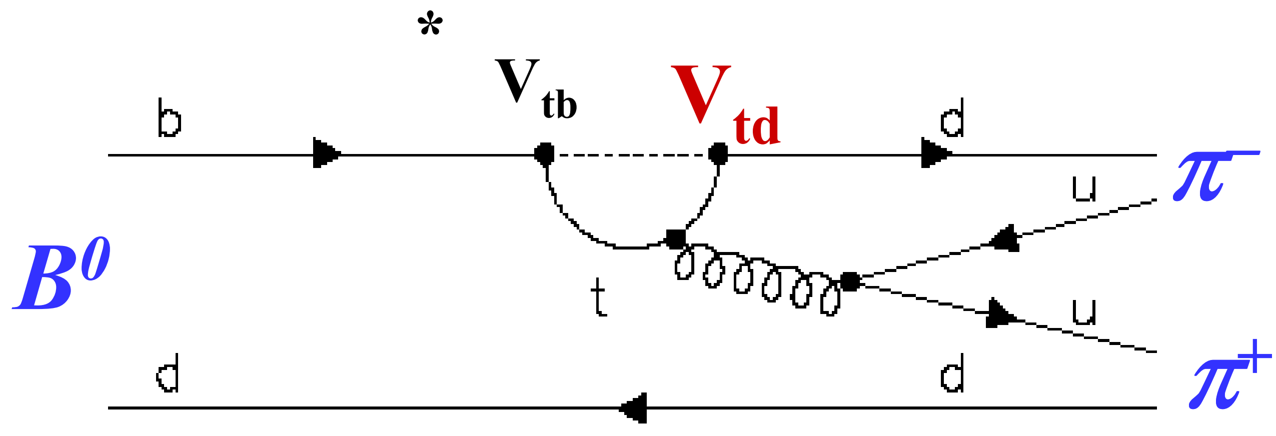
Super KEKB design parameters

Machine Parameters of the SuperKEKB

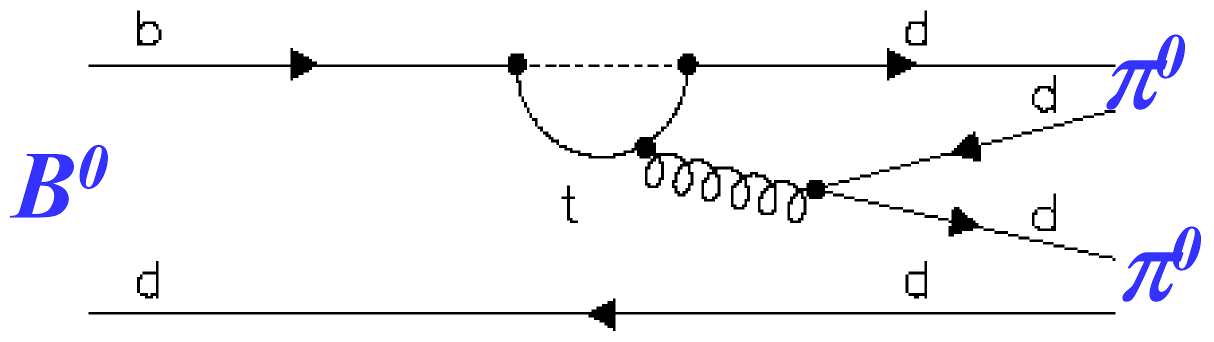
	LER	HER	
Horizontal Emittance	33	33	nm
Vertical Emittance	2.1	2.1	nm
x-y coupling	6.4	6.4	%
Beam current	9.4	4.1	A
Number of bunches	5018 (2% abort gap)		
Bunch current	1.87	0.817	mA
Bunch spacing	0.6		m
Half crossing angle	15		mrad
Luminosity reduction R_L	0.748		
ξ_x reduction $R_{\xi x}$	0.691		
ξ_y reduction $R_{\xi y}$	0.916		
Bunch length	3	3	mm
Radiation loss U_0	1.23	3.48	MeV/turn
Betatron tune ν_x / ν_y	45.515/43.57 ?	44.515/41.57 ?	
beta's at IP β_x^* / β_y^*	15/0.3	15/0.3	cm
beam-beam parameters ξ_x / ξ_y	0.068/0.05	0.068/0.05	
Beam lifetime	~150	~150	min.
Luminosity	1.0		10^{35}/cm^2/sec

Backup Slides

Must deal with “Penguin Pollution”



e.g. use $B\rightarrow\pi^0\ \pi^0$ to determine size of penguin effects:



(SM:~10^{-6})

Branching Fractions for B→π π Modes

If all three B→π π modes are measured, an isospin analysis allows the additional strong phase δ to be determined. Can then extract sin(2 φ_2).

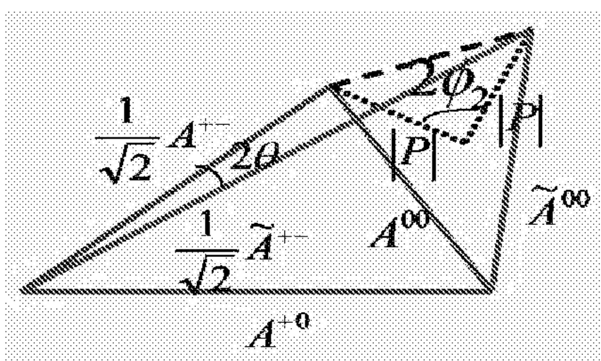
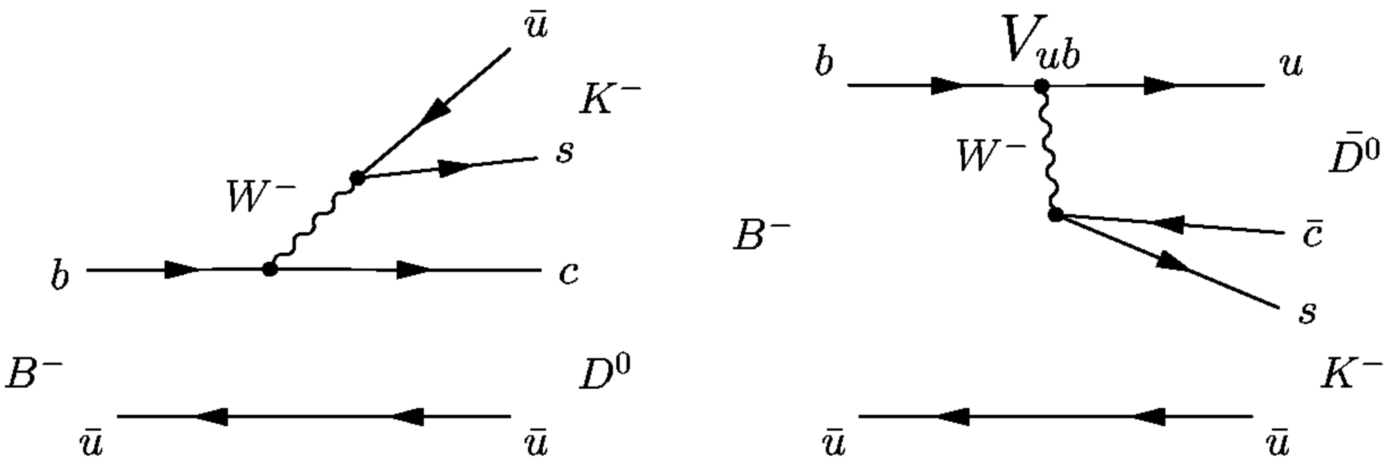


FIG. 10. The A and $\tilde{A}$ isospin triangles.

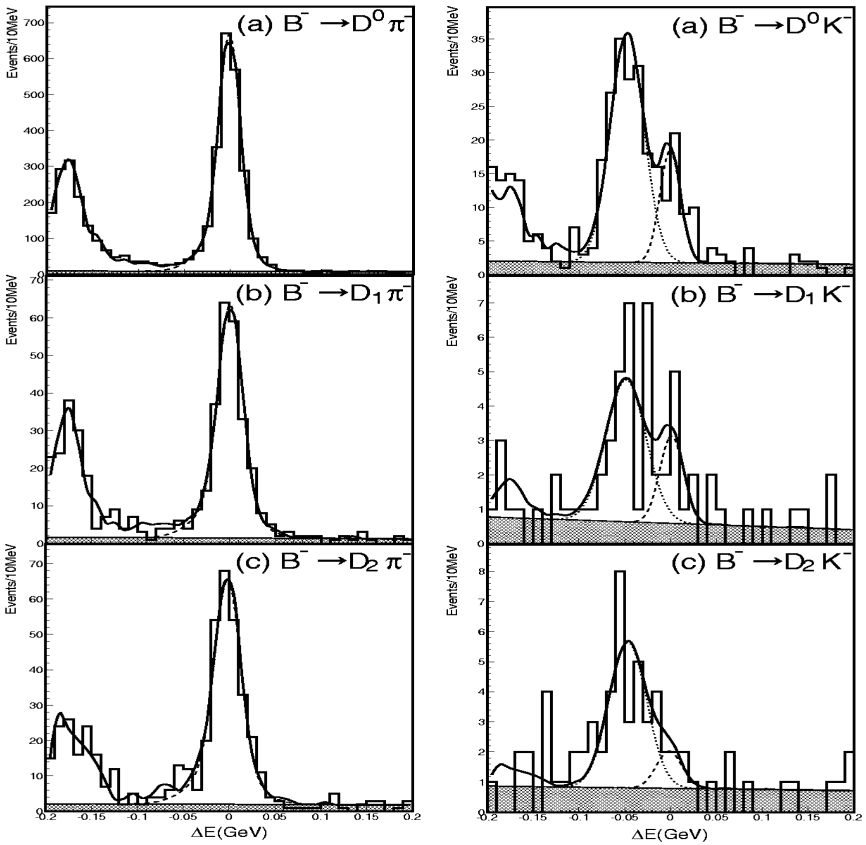
M. Gronau and D.London. PRL 65, 2381 (90)

Measuring φ_3 (γ) in D_{CP} K^- decays



When the D meson decays to a CP eigenstate, the two diagrams interfere. The interference depends on the phase of V_{ub} i.e. φ_3

BFs and Direct CPV in D_{CP} K^-



155.2+-13.6 $D^0 \to K^- \pi^+$

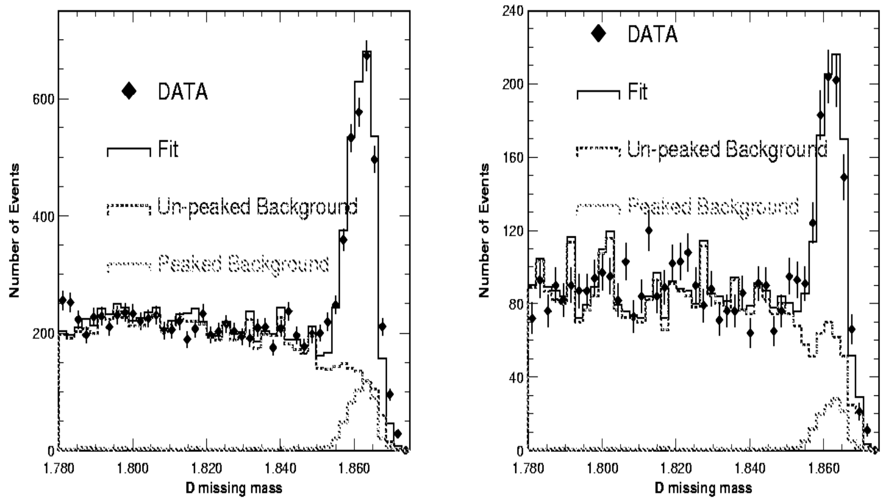
22.5+-5.7 CP=+1

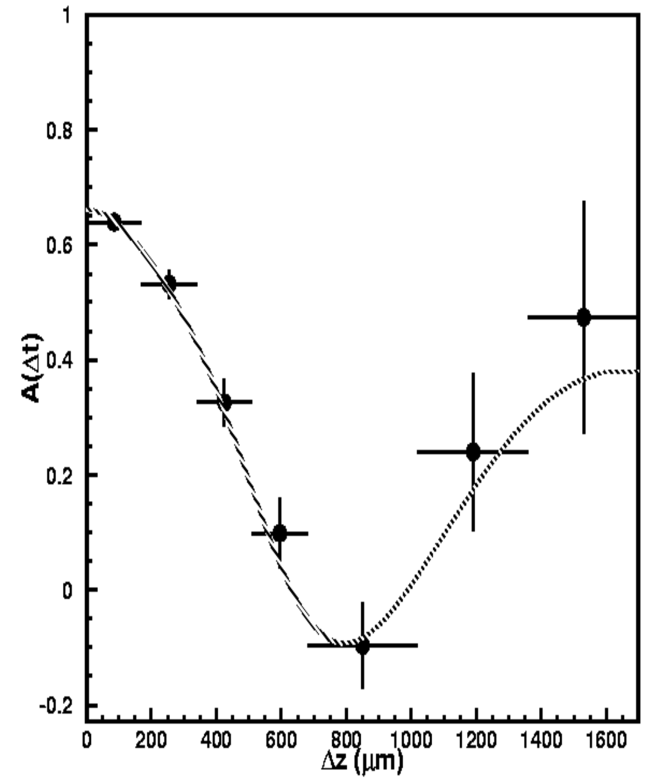
24.7+-6.1 CP=-1

BELLE-CONF-0108,

hep-ex/nnnn

$\sin(2\varphi_1 + \varphi_3)$ from $B^0 \to D^{*+} \pi^-$





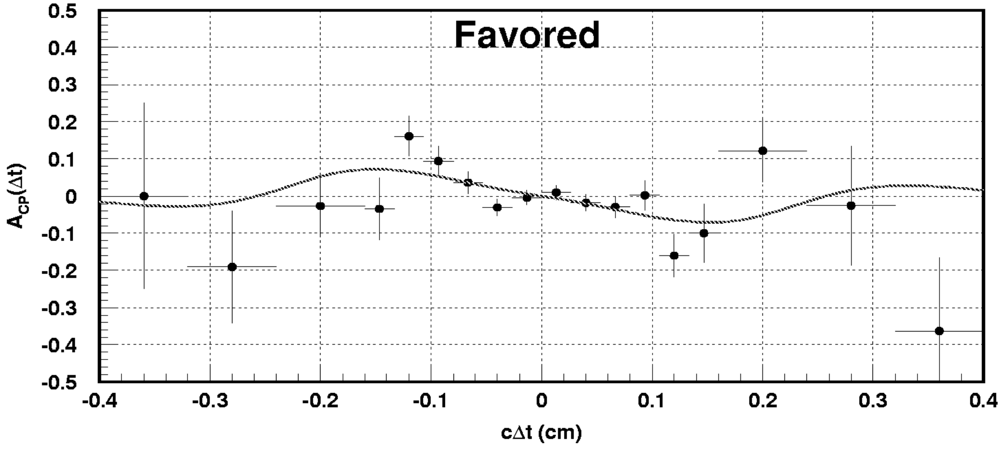
Feasibility study with mixing.

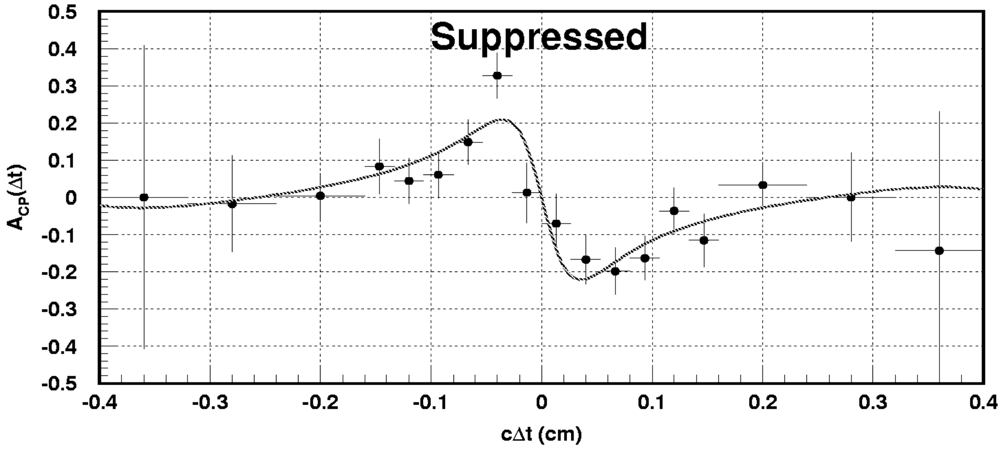
mixing freq Δm=0.517+-0.017(stat)+-0.019(sys)

hep-ex/0211065 to appear in PRD.

$\sin(2\varphi_1 + \varphi_3)$ from $B^0 \rightarrow D^{*+} \pi^-$

MC results





Sensitivity is +-0.34 with 200 fb^{-1}

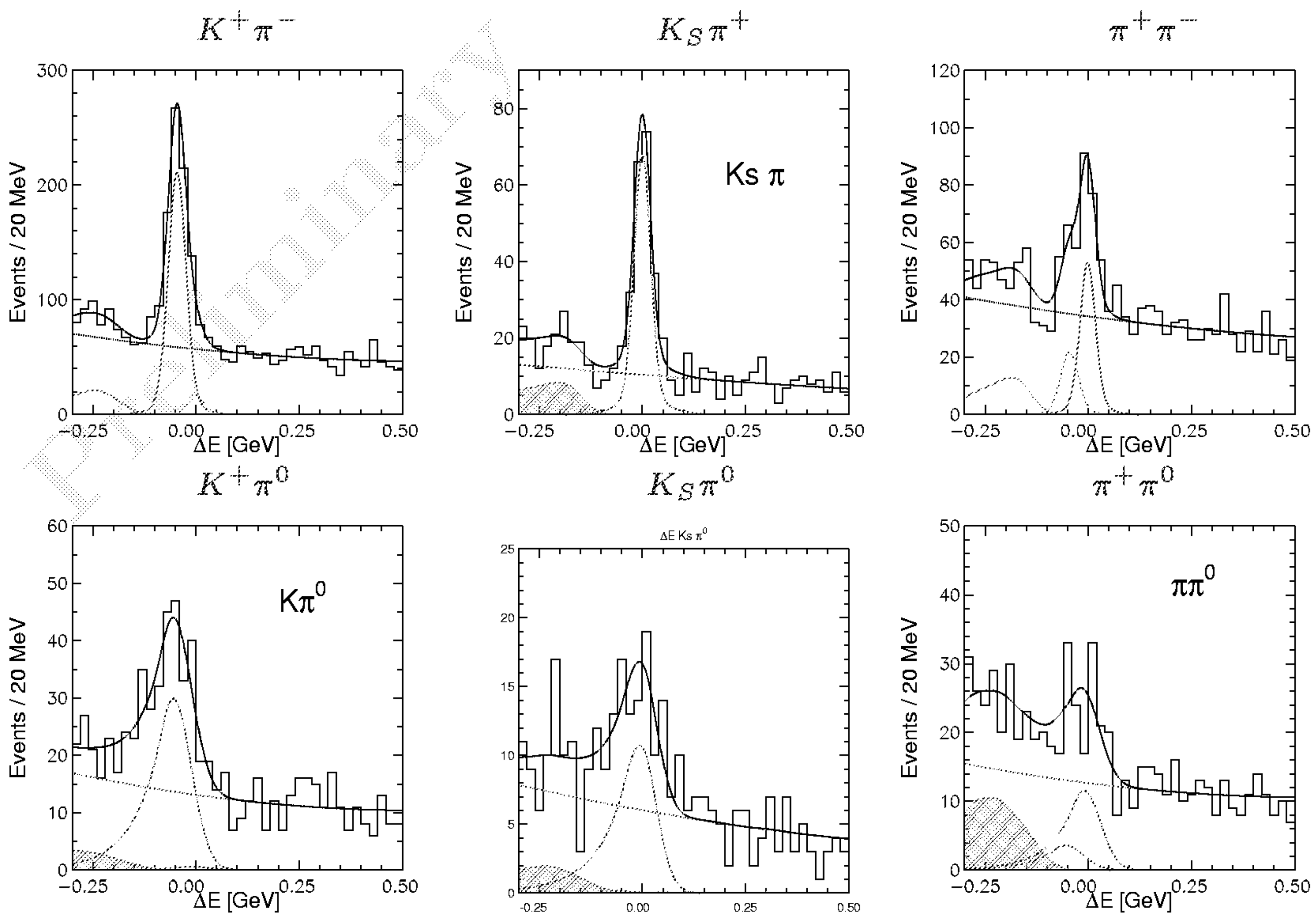
Direct CP Asymmetries for B→h h Modes

Mode	$N_s(\overline{B})$	$N_s(B)$	$\mathcal{A}_{CP}$	90% confidence intervel
$K^+\pi^-$	$235.4\ ^{+19.8}_{-19.1}$	$270.2\ ^{+19.7}_{-18.9}$	$-0.07 \pm 0.06 \pm 0.01$	$-0.18 < \mathcal{A}_{CP} < 0.04$
$K^+\pi^0$	122.0 ± 15.8	76.5 ± 14.5	$0.23 \pm 0.11\ ^{+0.01}_{-0.04}$	$-0.01 < \mathcal{A}_{CP} < 0.42$
$K^0\pi^+$	$119.1\ ^{+13.8}_{-13.1}$	$104.4\ ^{+13.2}_{-12.5}$	$0.07\ ^{+0.09}_{-0.08}\ ^{+0.01}_{-0.03}$	$-0.10 < \mathcal{A}_{CP} < 0.22$
$\pi^+\pi^0$	31.2 ± 11.9	41.3 ± 12.7	$-0.14 \pm 0.24\ ^{+0.05}_{-0.04}$	$-0.57 < \mathcal{A}_{CP} < 0.30$

Hint (~2.2 σ level) of direct CP violation in $B^0 \to \pi^+ \pi^-$: $A_{\pi\pi} = 0.77 \pm 0.27 \pm 0.08$

In the pure penguin mode $B^{\pm} \to K_S \pi^{\pm}$ no asymmetry observed with 78 fb^{-1}

Signals for B → h h Modes at 78 fb^{-1}



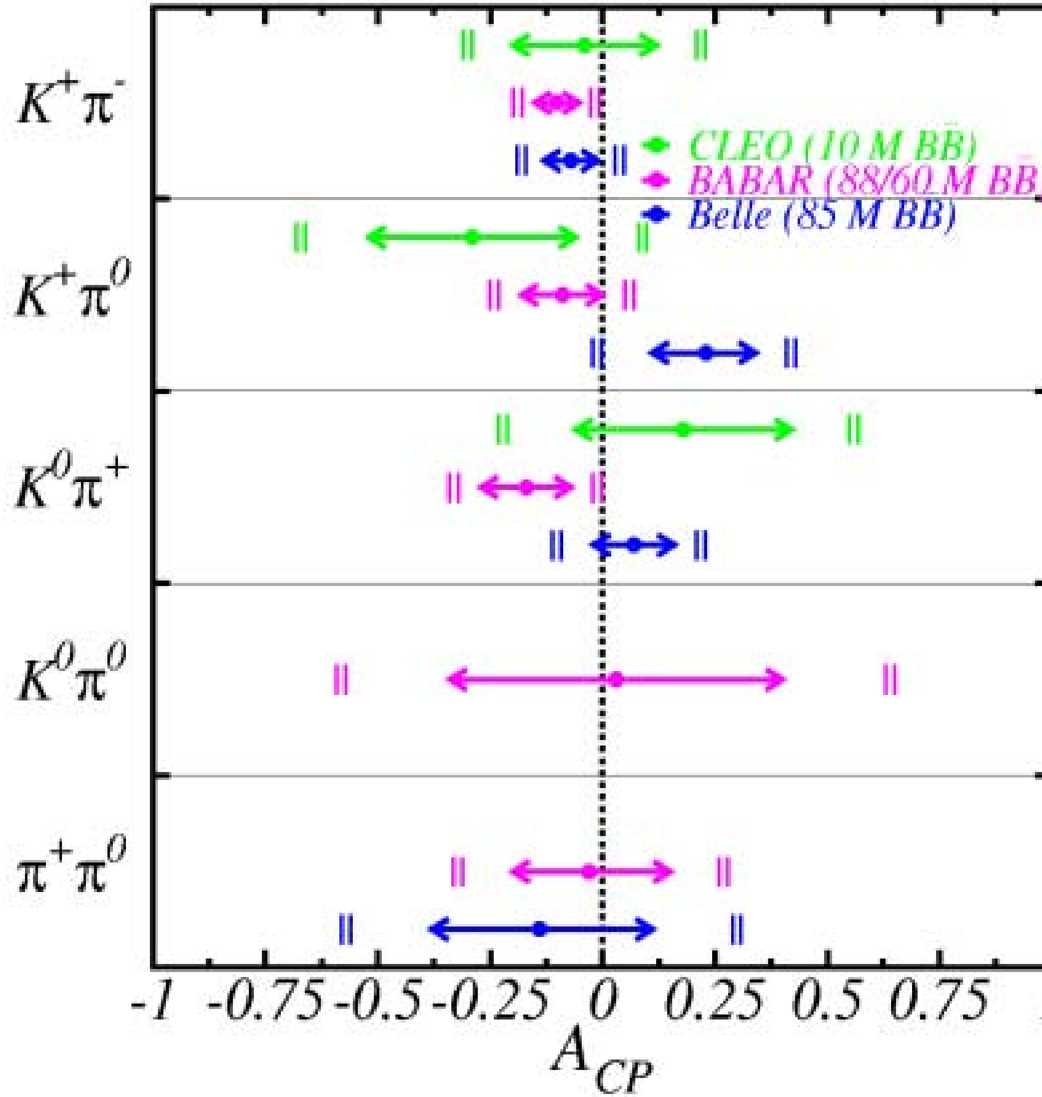
Sensitivity ±6 %

Sensitivity ±11 %

Pure penguin

Flavor tag required

Pure tree



Theoretical Expectations: 5-10 % in QCD Fact or pQCD

Systematic uncertainties*

source	$A_{\pi\pi}$		$S_{\pi\pi}$	
	+error	−error	+error	−error
Background fractions	+0.058	−0.048	+0.044	−0.055
Vertexing	+0.044	−0.054	+0.038	−0.012
Fit bias	+0.016	−0.021	+0.052	−0.020
Wrong tag fraction	+0.026	−0.021	+0.015	−0.016
τ_B, Δm_d, $A_{K\pi}$	+0.021	−0.014	+0.022	−0.022
Resolution function	+0.019	−0.020	+0.010	−0.013
Background shape	+0.003	−0.015	+0.007	−0.002
Total	**+0.08**	**−0.08**	**+0.08**	**−0.07**

* blind analysis: actual estimations done before seeing fit result.

Constraints on the CKM angle ϕ_2

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

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

$$\lambda_{\pi\pi} = e^{i\phi_2}\frac{1+|P/T|e^{i(\delta+\phi_3)}}{1+|P/T|e^{i(\delta-\phi_3)}}$$

convention taken from M.Gronau & J.L.Rosner Phys Rev D65, 093012 (2002)

4 parameters

$$S_{\pi\pi} = [\sin 2\phi_2 + 2|P/T|\sin(\phi_1 - \phi_2)\cos\delta - |P/T|^2 \sin 2\phi_1]/R_{\pi\pi},$$

$$A_{\pi\pi} = -[2|P/T|\sin(\phi_1+\phi_2)\sin\delta]/R_{\pi\pi},$$

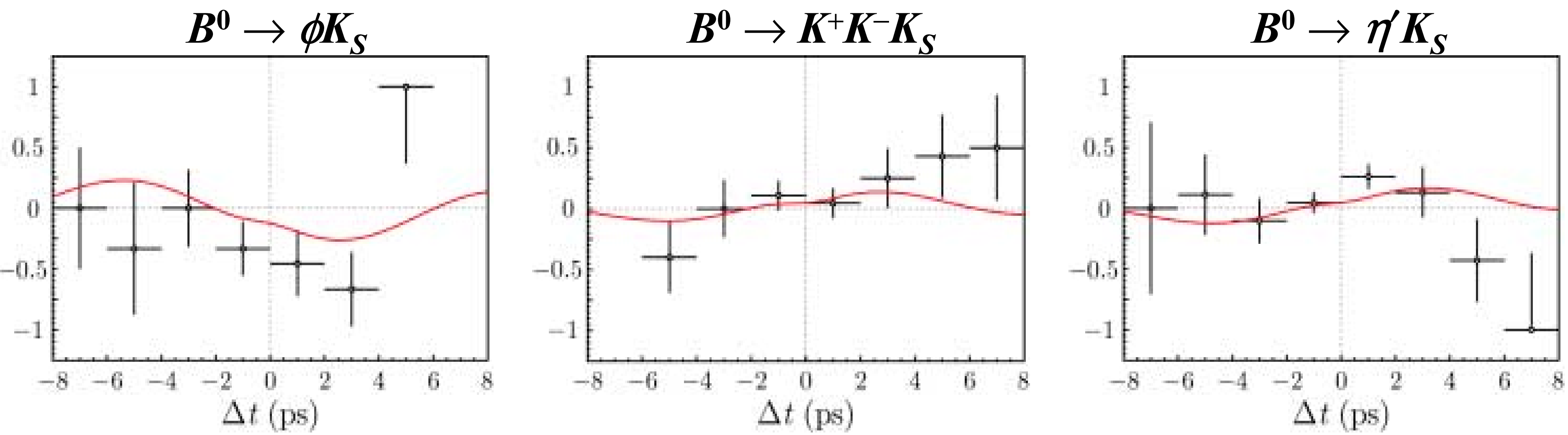
$$R_{\pi\pi} = 1 - 2|P/T|\cos(\phi_1+\phi_2)\cos\delta + |P/T|^2$$

$$\delta \equiv \delta_P - \delta_T$$

|P/T|	0.15-0.45 (representative)	Theory ~0.3
ϕ_1	21.3 - 25.9deg	(Belle & BaBar combined)

CP Violation in $b \to s s \bar{s}$

@ 78 fb^{-1}



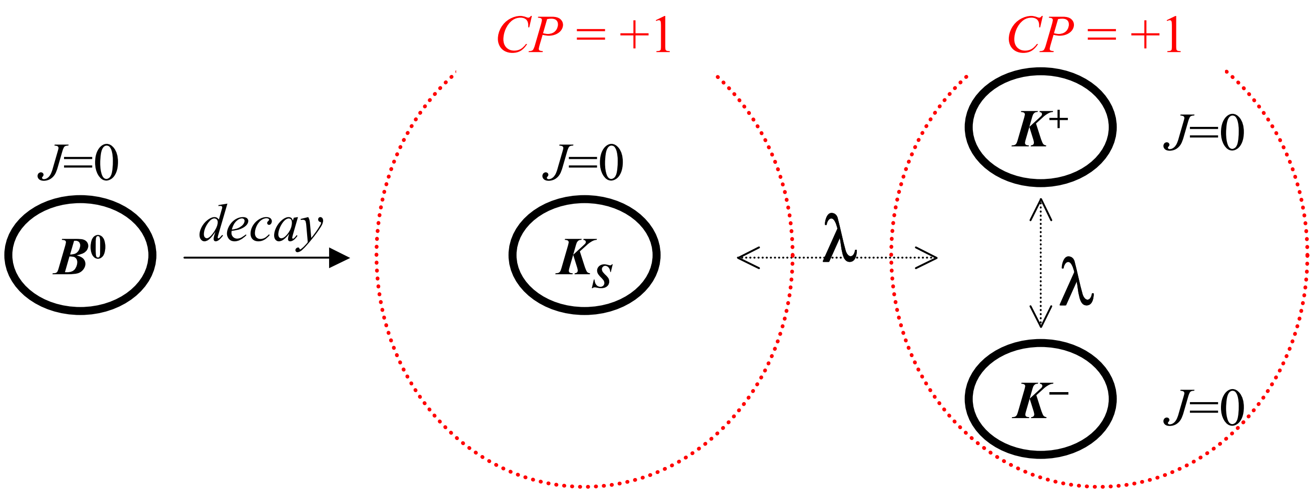
	$B^0 \to \phi K_S$	$B^0 \to K^+K^-K_S$	$B^0 \to \eta' K_S$
	$-0.73 \pm 0.64 \pm 0.22$	$+0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$	$+0.71 \pm 0.37\,^{+0.05}_{-0.06}$
A	$-0.56 \pm 0.41 \pm 0.16$	$-0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}$	$+0.26 \pm 0.22 \pm 0.03$

K. Abe *et al*. [Belle Collaboration], Phys. Rev. D **67**, 031102(R) (2003)

$B^0 \to K^+K^-K_S$: $CP = \pm 1$ Mixture

Since $B^0 \to K^+K^-K_S$ is 3-body decay,
the final state is a mixture of $CP = \pm 1$.
How can we determine the mixing fraction?

$CP = \pm 1$ fraction is equal to that of λ=even/odd



$CP = (-1)^\lambda$

$B^0 \to K^+K^-K_S$: $CP = \pm 1$ Mixture

λ-even fraction in $|K^0\overline{K}^0\rangle$ can be determined by $|K_SK_S\rangle$ system

$$\left|K^0\overline{K}^0\right\rangle = \frac{a}{\sqrt{2}}\left(\left|K_SK_S\right\rangle + \left|K_LK_L\right\rangle\right) + b\left|K_SK_L\right\rangle$$

$CP = +1$ λ = even λ = odd

Add K^+ to above kets

$$\left|K^+K^0\overline{K}^0\right\rangle = \frac{a}{\sqrt{2}}\left(\left|K^+K_SK_S\right\rangle + \left|K^+K_LK_L\right\rangle\right) + b\left|K^+K_SK_L\right\rangle$$

Using isospin symmetry

$$\mathcal{B}(B^+ \to K^+K^0\overline{K}^0) = \mathcal{B}(B^0 \to K^0K^+K^-) \times \frac{\tau_{B^+}}{\tau_{B^0}} = \frac{\mathcal{B}(B^0 \to K_SK^+K^-)}{2} \times \frac{\tau_{B^+}}{\tau_{B^0}}$$

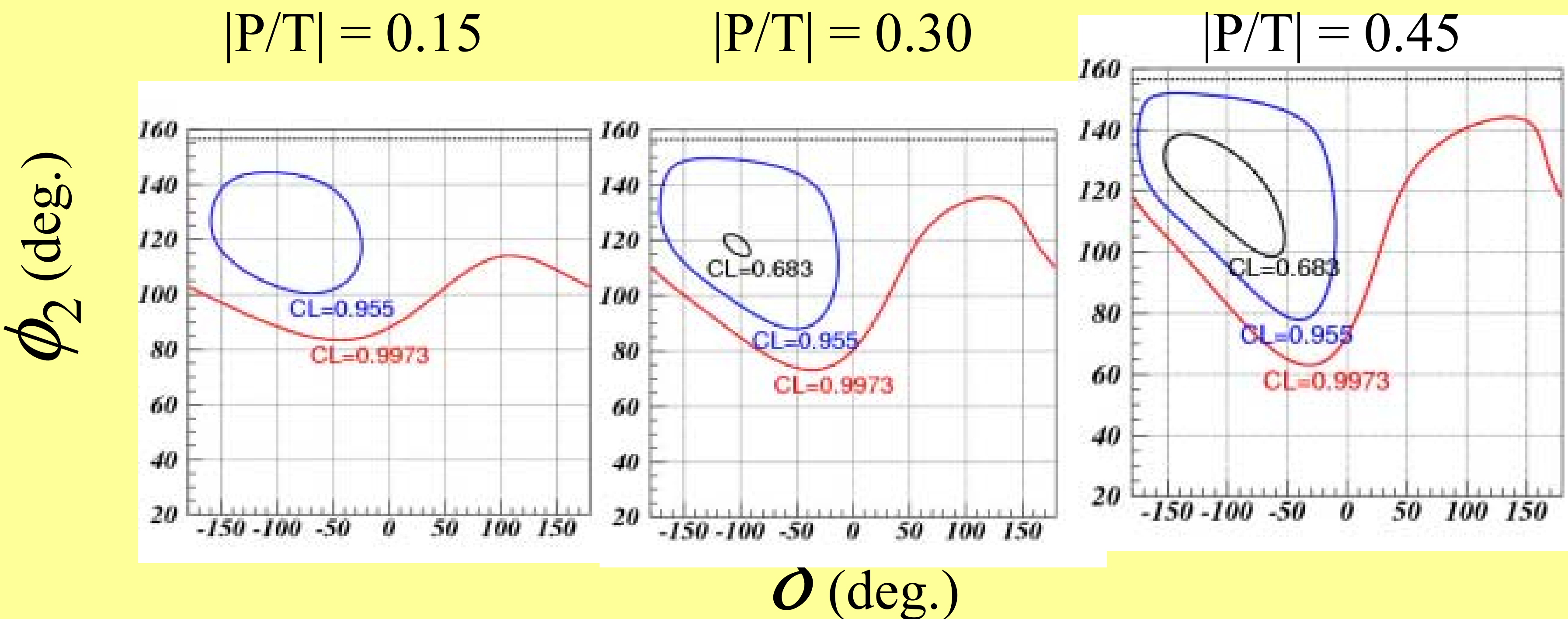
$$a^2 = 2\frac{\mathcal{B}(B^+ \to K^+K_SK_S)}{\mathcal{B}(B^0 \to K^0K^+K^-)} \times \frac{\tau_{B^0}}{\tau_{B^+}} = \frac{\mathcal{B}(B^+ \to K^+K_SK_S)}{\mathcal{B}(B^0 \to K_SK^+K^-)} \times \frac{\tau_{B^0}}{\tau_{B^+}}$$

$$= 1.04 \pm 0.19(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

100^{+0}_{-20} % *CP* even

Constraints on ϕ_2 (cont'd)

|P/T| dependence ($\phi_1 = 23.5°$)



- Consistent with theoretical predictions
- Larger |P/T| favored

TABLE III: The fractions of MC pseudo-experiments outside the physical boundary and above the CP violation we observe for various input values. $\rho_{\pi\pi} = \sqrt{\mathcal{A}_{\pi\pi}^2 + \mathcal{S}_{\pi\pi}^2}$. The selected points are on the line segment between $(\mathcal{A}_{\pi\pi}, \mathcal{S}_{\pi\pi}) = (0,0)$ and $(+0.57, -0.82)$.

Input $\rho_{\pi\pi}$	The fractions outside the physical boundary (%)	The fractions above the CP violation we observe (%)
0.00	1.8	0.07
0.20	3.3	0.17
0.40	7.3	0.62
0.60	16.4	1.7
0.80	34.4	6.0
1.00	60.1	16.6

Statistical Issues: Likelihood for B→ππ

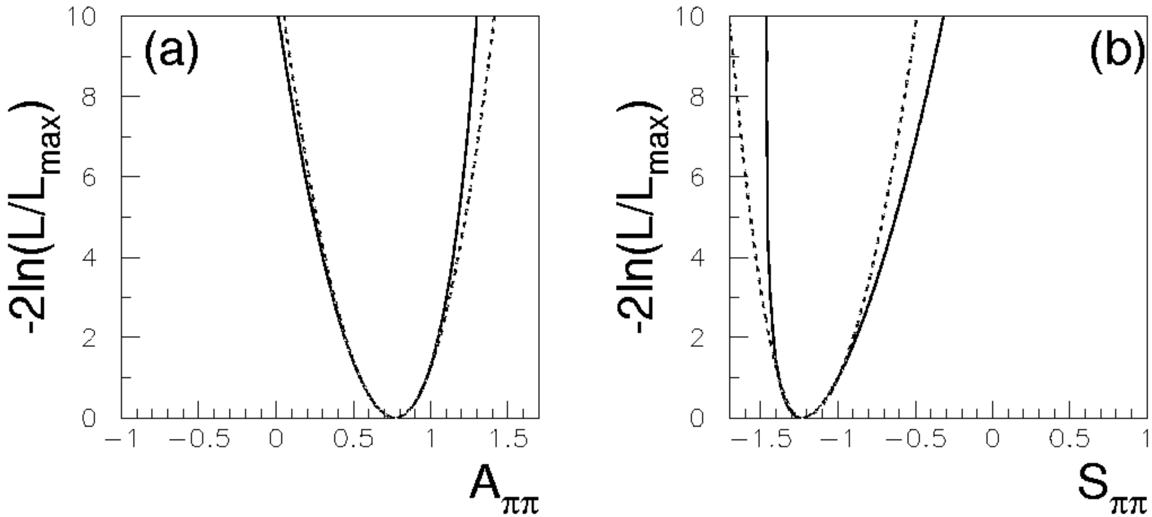


FIG. 3: (a) The value of $-2\ln(\mathcal{L}/\mathcal{L}_{\rm max})$ vs. $\mathcal{A}_{\pi\pi}$ and (b) the value of $-2\ln(\mathcal{L}/\mathcal{L}_{\rm max})$ vs. $\mathcal{S}_{\pi\pi}$. The dotted curves represent parabolic functions which pass the point at 1σ.

Errors for B→ππ in data and toy MC

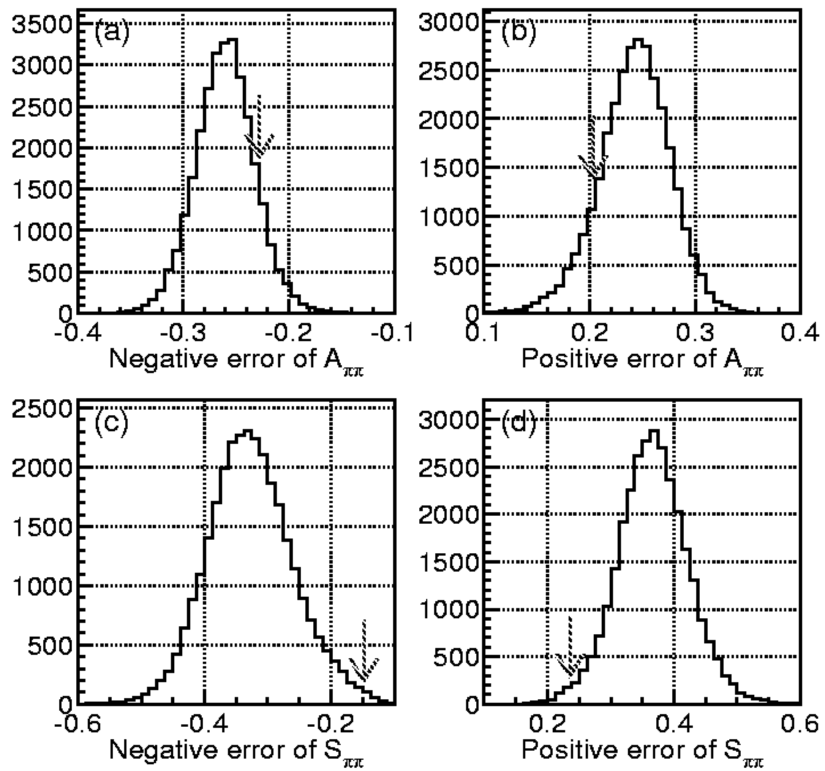
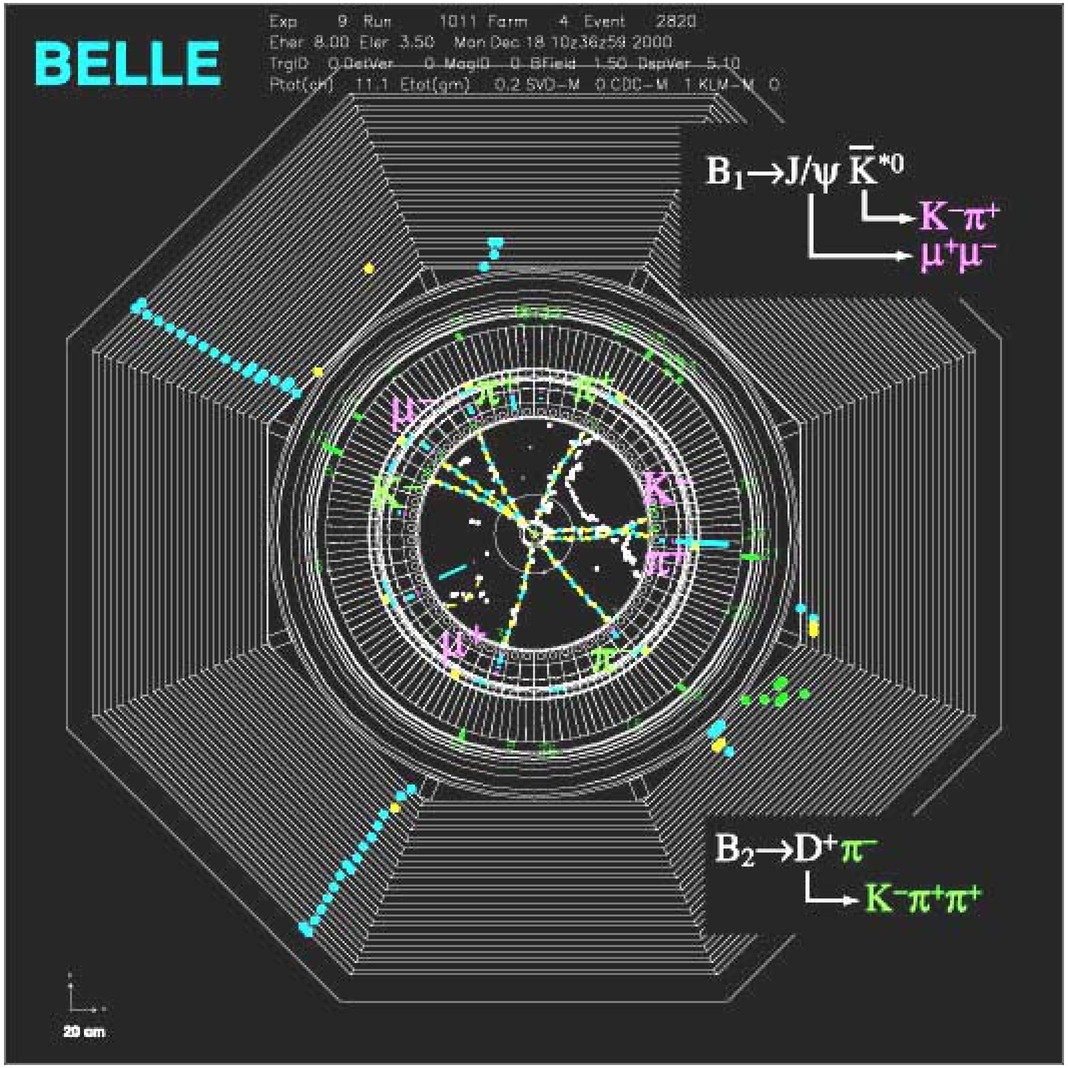
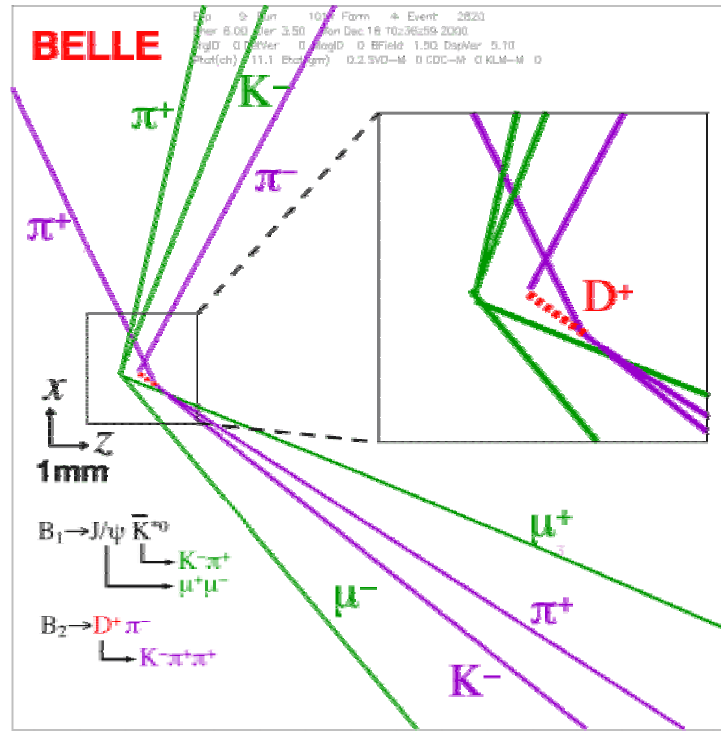


FIG. 4: The result of MC pseudo-experiments with input values of $\mathcal{A}_{\pi\pi} = +0.57$ and $\mathcal{S}_{\pi\pi} = -0.82$: the distributions of (a) the negative and (b) positive MINOS errors of $\mathcal{A}_{\pi\pi}$, and (c) the negative and (d) positive MINOS errors of $\mathcal{S}_{\pi\pi}$. The arrows indicate the MINOS errors obtained from the fit to data.

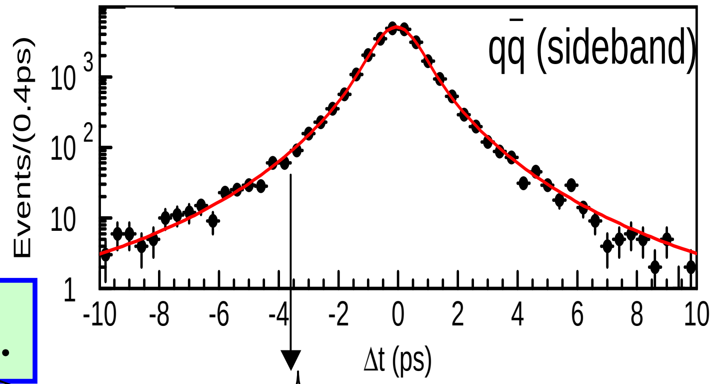
Example of a Fully-reconstructed Event





Time Dependent Likelihood Fit

2 free parameters ($A_{\pi\pi}$, $S_{\pi\pi}$) in the final fit



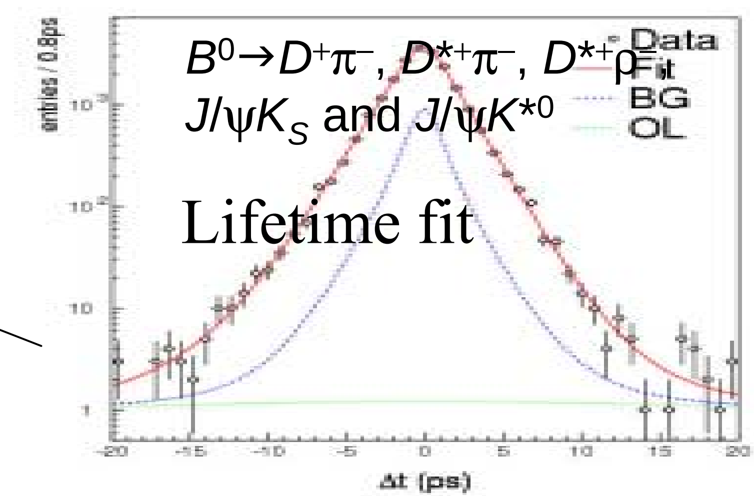
ΔE-M_{bc} dist.

$$L = \Pi_i P_i$$

$$P_i = (1 - f_{ol}) \int_{-\infty}^{+\infty} \{ (f_{\pi\pi}^m P_{\pi\pi}^q + f_{K\pi}^m P_{K\pi}) \cdot R_{sig} + f_{q\bar{q}}^m P_{q\bar{q}} \cdot R_{q\bar{q}} \} d\Delta t'$$

$$+ f_{ol} \cdot P_{ol}(\Delta t_i)$$

(single Gaussian outlier)



Dependence of the results on cuts

TABLE V: Selection-requirement dependence of $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ (MINOS errors only).

Cut value	$\mathcal{A}_{\pi\pi}$	$\mathcal{S}_{\pi\pi}$
default (KID < 0.4)	$0.77^{+0.20}_{-0.23}$	$-1.23^{+0.24}_{-0.15}$
$\lvert\Delta E\rvert < 2\sigma$	$0.81^{+0.20}_{-0.22}$	$-1.21^{+0.25}_{-0.16}$
$\lvert\Delta E\rvert < 1\sigma$	$0.82^{+0.21}_{-0.25}$	$-1.18^{+0.29}_{-0.19}$
KID < 0.20	$0.74^{+0.20}_{-0.23}$	$-1.11^{+0.26}_{-0.17}$
KID < 0.15	$0.59^{+0.22}_{-0.24}$	$-1.14^{+0.23}_{-0.14}$
$LR > 0.825$	$0.84^{+0.22}_{-0.25}$	$-1.19^{+0.27}_{-0.18}$
$LR > 0.925$	$0.69^{+0.26}_{-0.30}$	$-1.24^{+0.30}_{-0.19}$
$\lvert qr\rvert > 0.75$	$1.02^{+0.19}_{-0.25}$	$-1.24^{+0.19}_{-0.25}$
$\lvert qr\rvert > 0.875$	$0.91^{+0.24}_{-0.31}$	$-1.18^{+0.24}_{-0.31}$
$\lvert\Delta t\rvert < 15$ ps	$0.77^{+0.20}_{-0.23}$	$-1.25^{+0.24}_{-0.15}$
$\lvert\Delta t\rvert < 5$ ps	$0.76^{+0.20}_{-0.22}$	$-1.27^{+0.26}_{-0.17}$
Sample I (42 fb^{-1})	$1.00^{+0.19}_{-0.25}$	$-1.14^{+0.30}_{-0.21}$
Sample II (36 fb^{-1})	$0.37^{+0.32}_{-0.33}$	$-1.99^{+0.70}_{-0.65}$