Measurements of $\phi_1(\beta)$ at Belle

Ryosuke Itoh, KEK

representing
The Belle Collabration

Beauty 2005
Assisi, Perugia, Italy
6/20/2005

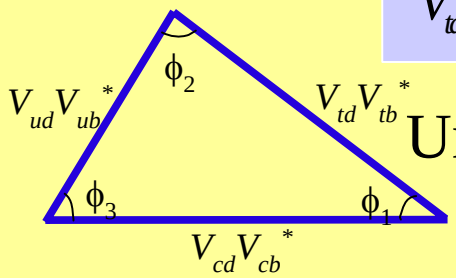
Outline

1. Introduction
2. Experimental Apparatus
3. Measurement of ϕ_1 in b$\rightarrow$c transitions
4. Measurement of ϕ_1 in b$\rightarrow$s transitions
5. Future plan of ϕ_1 measurements
6. Summary

1. Introduction

- The goal of B-factory experiment is the precise determination of the unitarity triangle

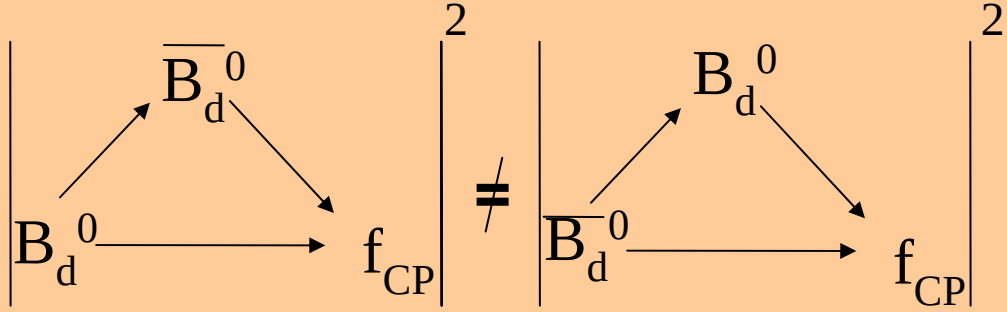
$$V_{td}V_{tb}^{*}+V_{cd}V_{cb}^{*}+V_{ud}V_{ub}^{*}=1$$



Unitarity Triangle

CP Violation ≡ non-zero angle

Mixing induced CP Violation

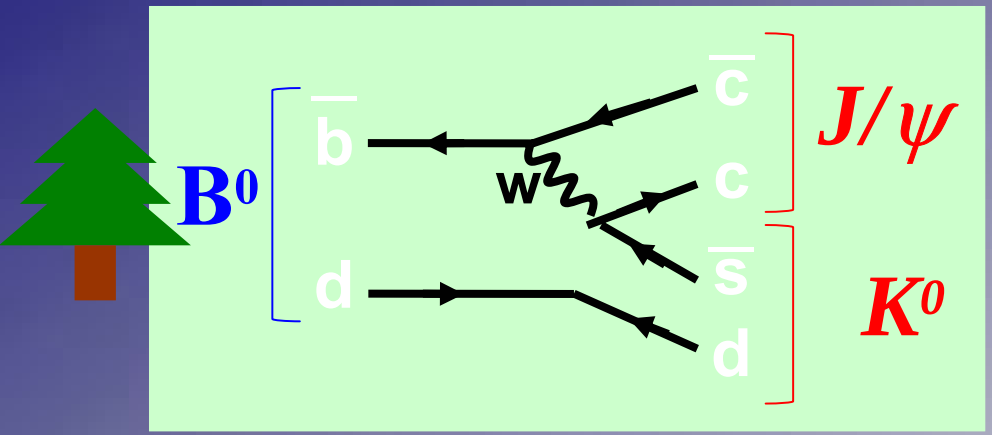


$$A_{CP}(\Delta t)=\frac{\Gamma(B_d^0\to f_{CP})-\Gamma(\overline{B^0}_d\to f_{CP})}{\Gamma(B_d^0\to f_{CP})+\Gamma(\overline{B^0}_d\to f_{CP})}=S_{CP}\sin(\Delta m\Delta t)+A_{CP}\cos(\Delta m\Delta t)$$

S_{CP}: $-\xi\sin2\phi_1$; A_{CP}: 0 ; SM

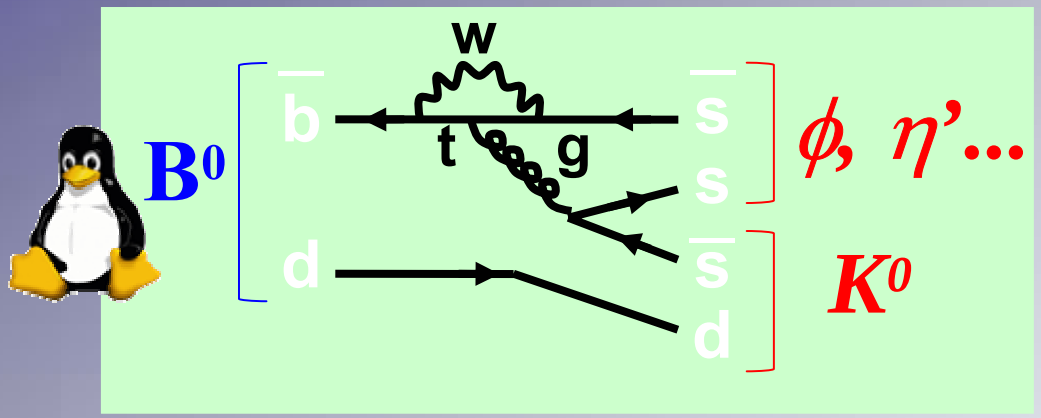
- $\sin2\phi_1$ → non 0 value (CPV) is established in b → c transitions.
  → precision measurement as a reference
- Probing new physics effects in FCNC (b→s penguin)
  by comparing measured $\sin2\phi_1$ with the reference from b→c.

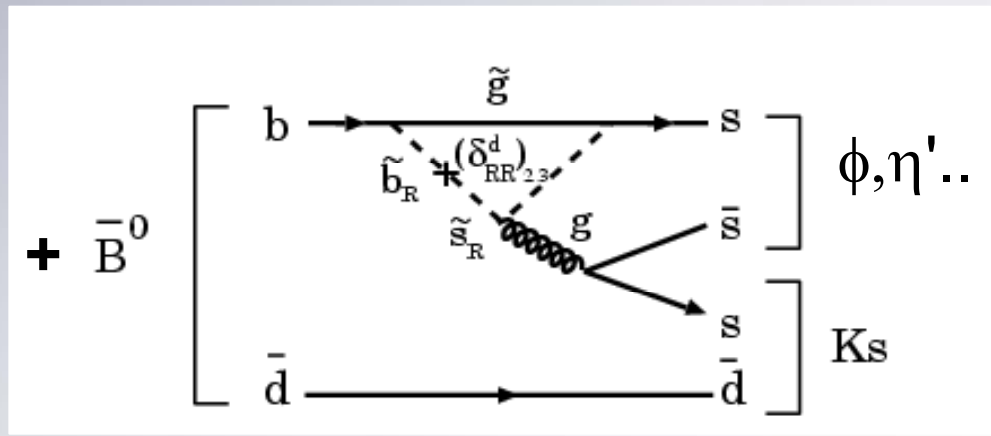
b→c transition



- Tree diagram dominates.
- Negligible uncertainty from Penguins.

b→s transition



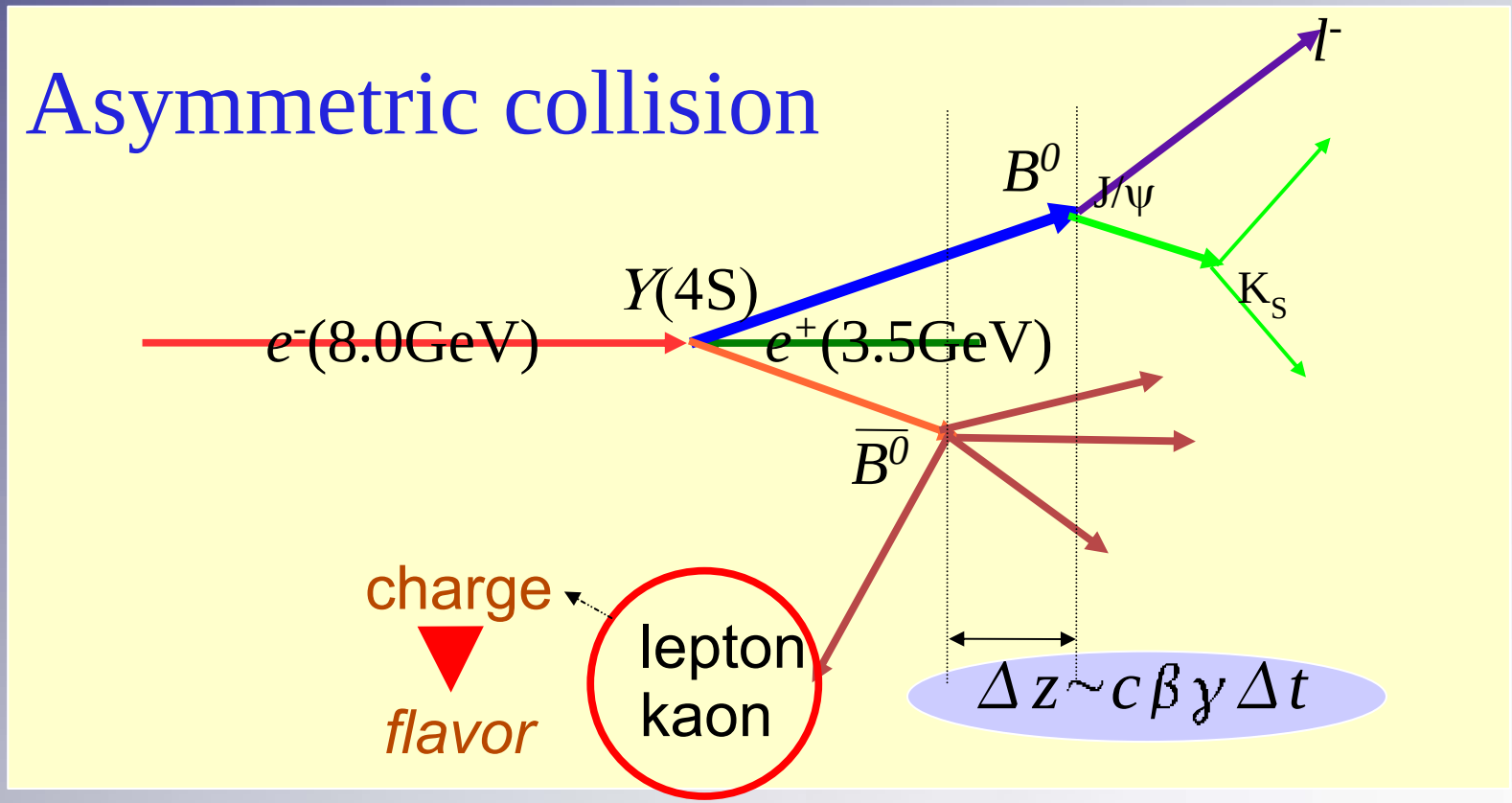


sin2ϕ_1(b→s) :
Sensitive probe of New Physics

New coupling →New Phase
sin2ϕ_1(b→c) ≠ sin2ϕ_1(b→s)

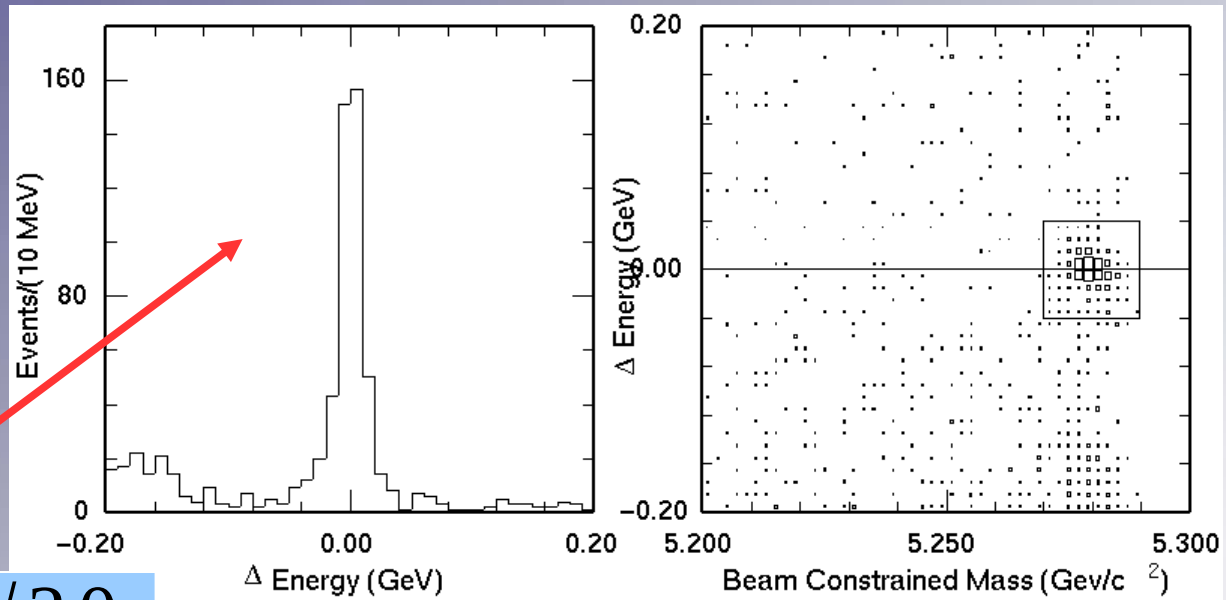
Measurement Technique

- B^0 and $\overline{B^0}$ mesons are produced from $\Upsilon(4S)$ decay at B-factories.
- To measure A_{CP}, we need to know decay time difference (Δt) of two B^0 mesons with the flavor of one tagged.



Reconstruction of B meson

- Performed using special kinematics on $\Upsilon(4S)$

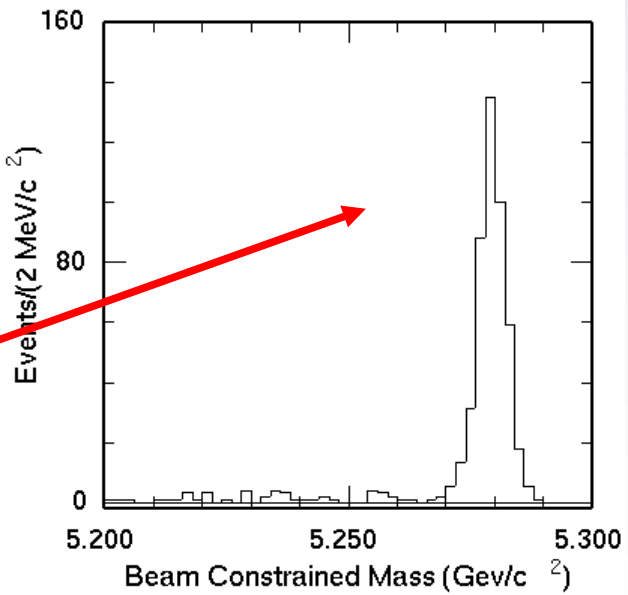


Energy difference:

$$\Delta E = \{ E_{J/\psi} + E_{Ks} \} - E_{CM}/2.0$$

energy of B^0 candidate

expected energy of B^0



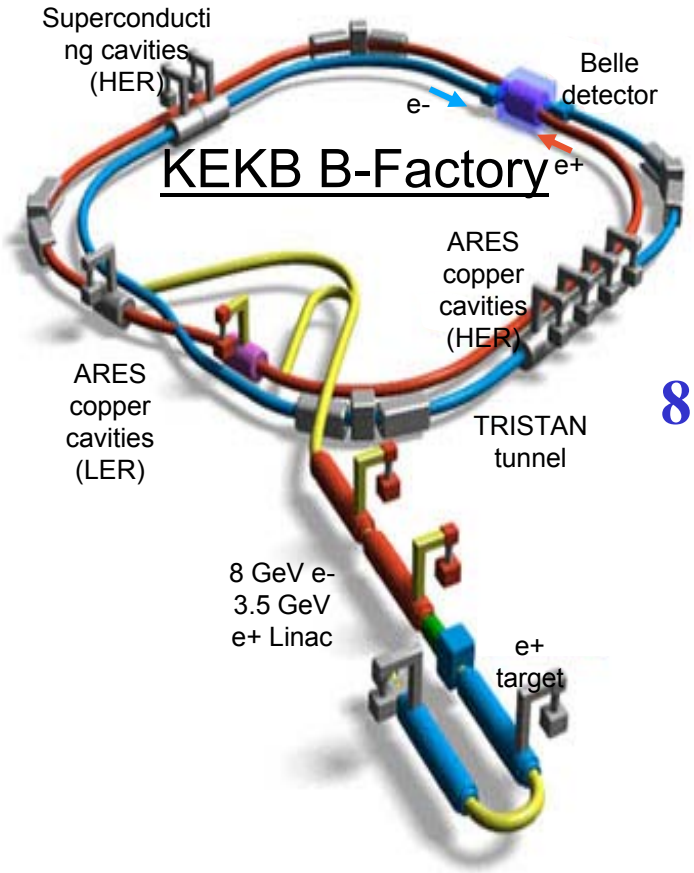
Beam Constrained Mass:

$$M_{bc} = \sqrt{\{ E_{CM}/2.0 \}^2 - \{ p_{J/\psi} + p_{Ks} \}^2}$$

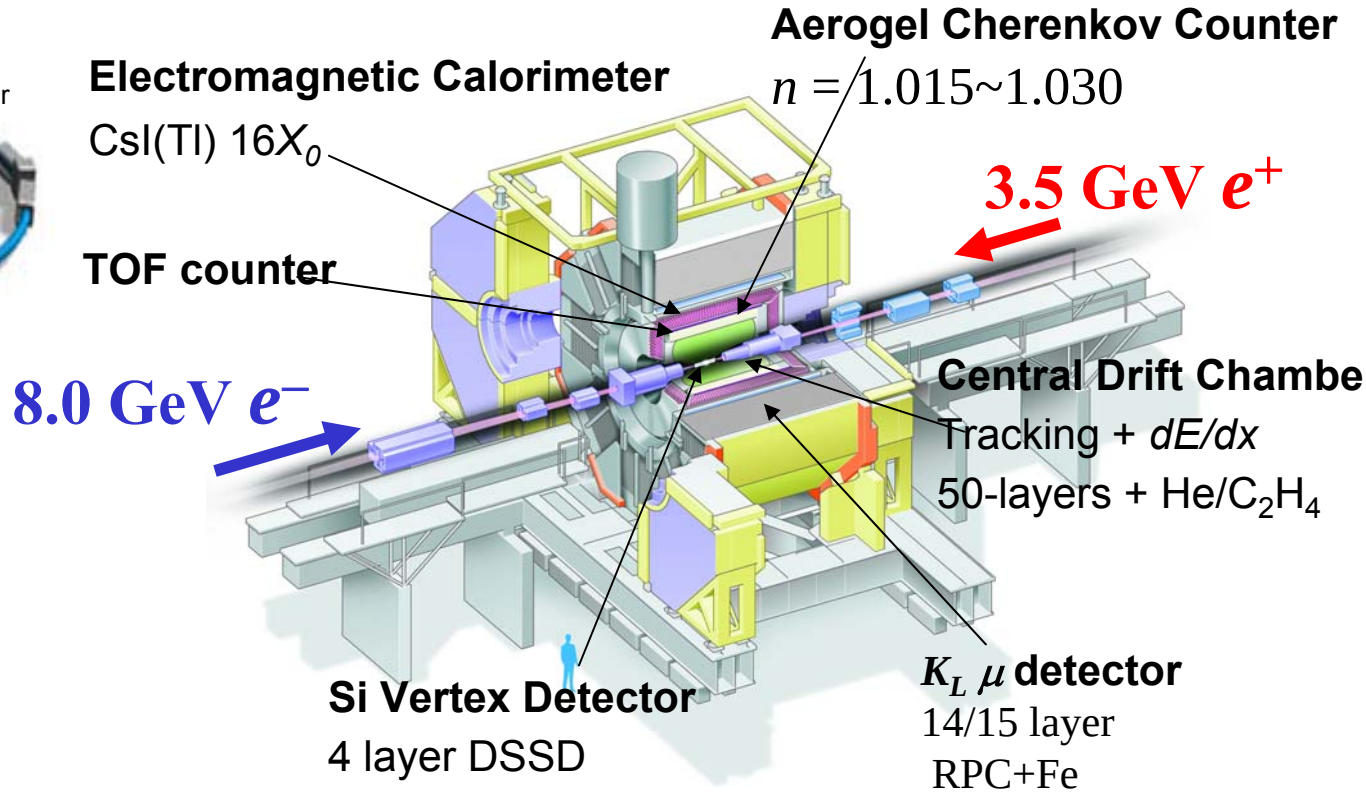
momentum of B^0 candidate

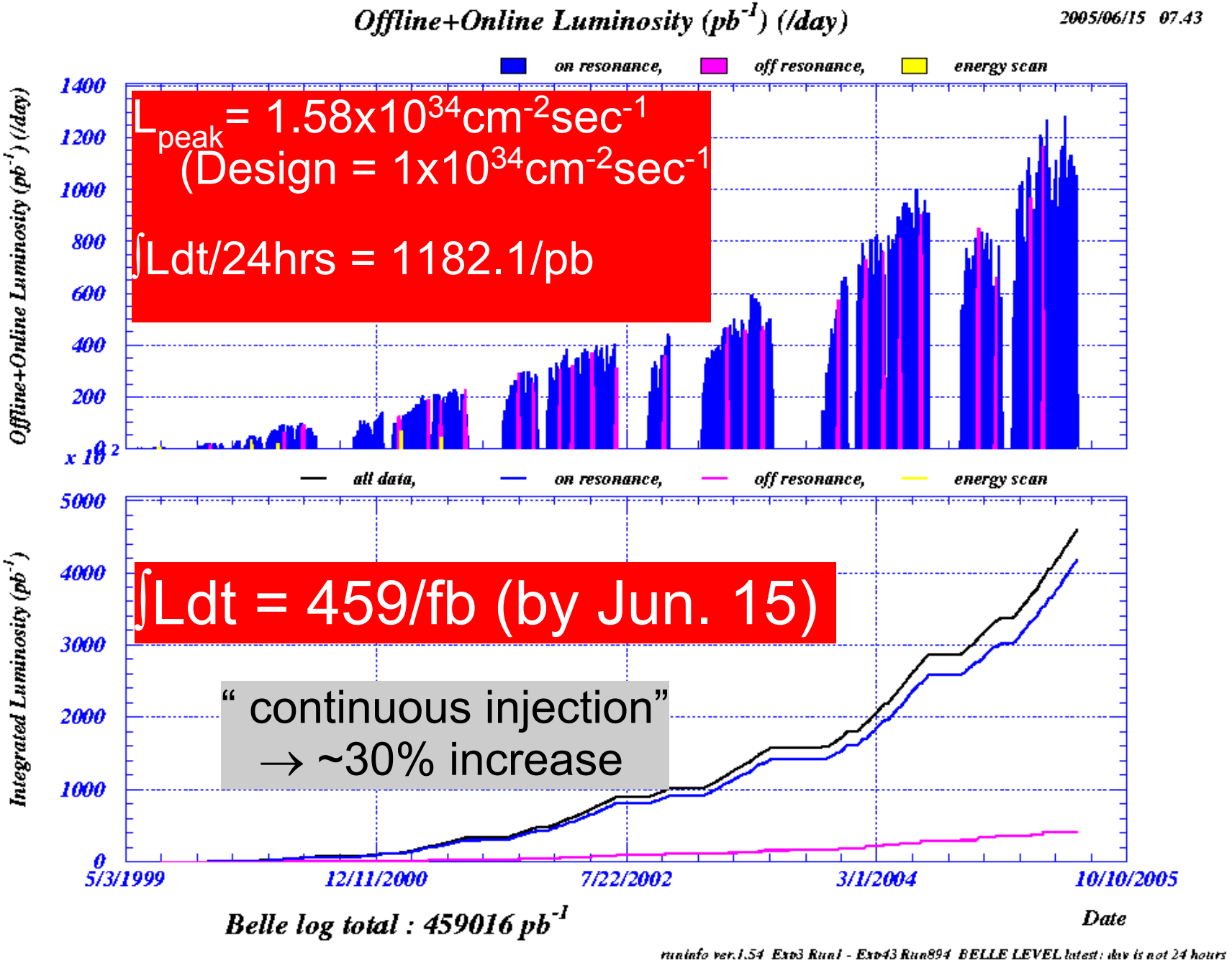
2. Experimental Setup

KEKB Accelerator



Belle Detector

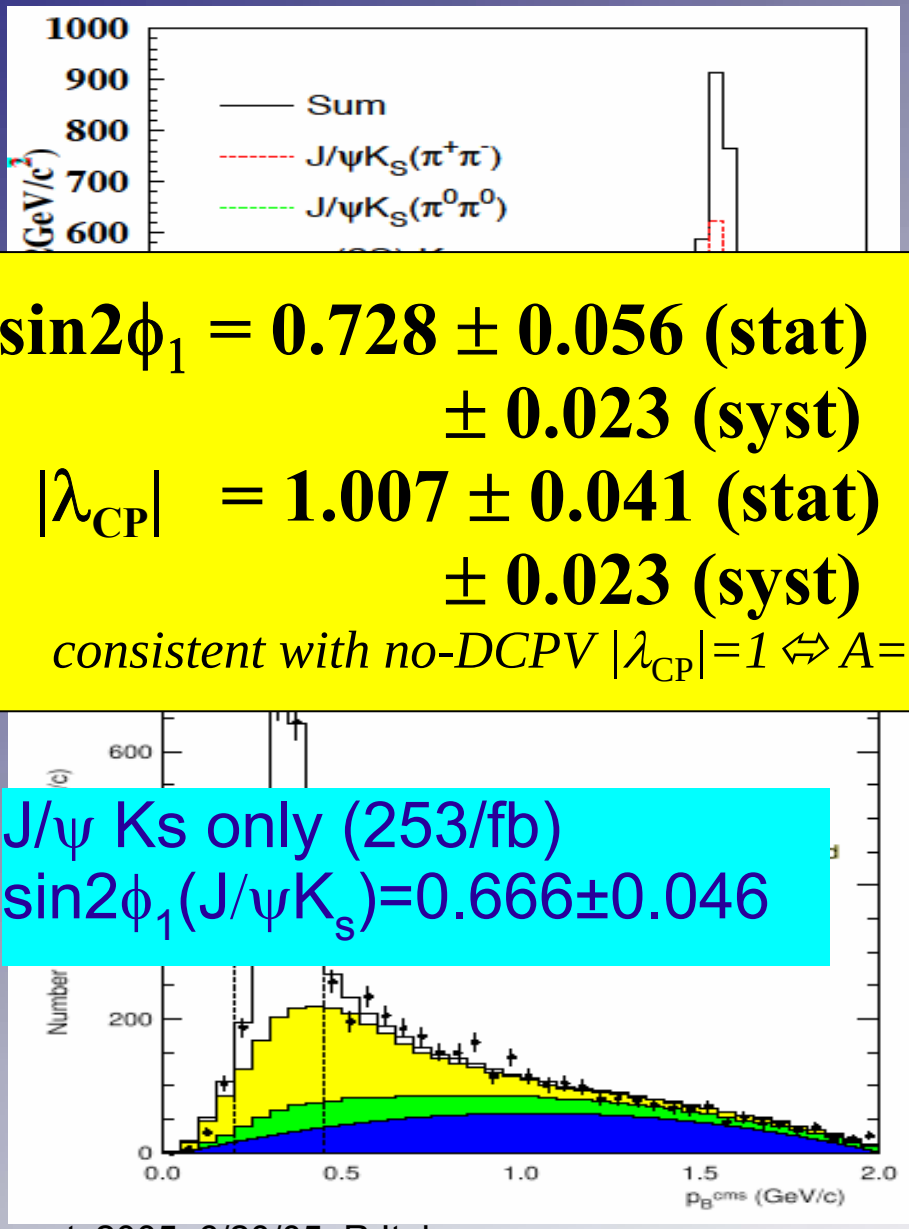



Offline+Online Luminosity (pb-1) (/day)
2005/06/15 07.43
on resonance,
off resonance,
energy scan
Offline+Online Luminosity (pb-1) (/day)
1400
1200
1000
800
600
400
200
0
x 10 2
Lpeak = 1.58x10^34cm^-2sec^-1
(Design = 1x10^34cm^-2sec^-1
∫Ldt/24hrs = 1182.1/pb
all data,
on resonance,
off resonance,
energy scan
Integrated Luminosity (pb-1)
5000
4000
3000
2000
1000
0
∫Ldt = 459/fb (by Jun. 15)
" continuous injection"
→ ~30% increase
5/3/1999
12/11/2000
7/22/2002
3/1/2004
10/10/2005
Belle log total : 459016 pb-1
Date
runinfo ver.1.54 Exp3 Run1 - Exp43 Run894 BELLE LEVEL latest: day is not 24 hours

3. Measurement of ϕ_1 in b→c transitions

Data Sample : 140/fb; 4347 signals

PRD 71, 072003 (2005)



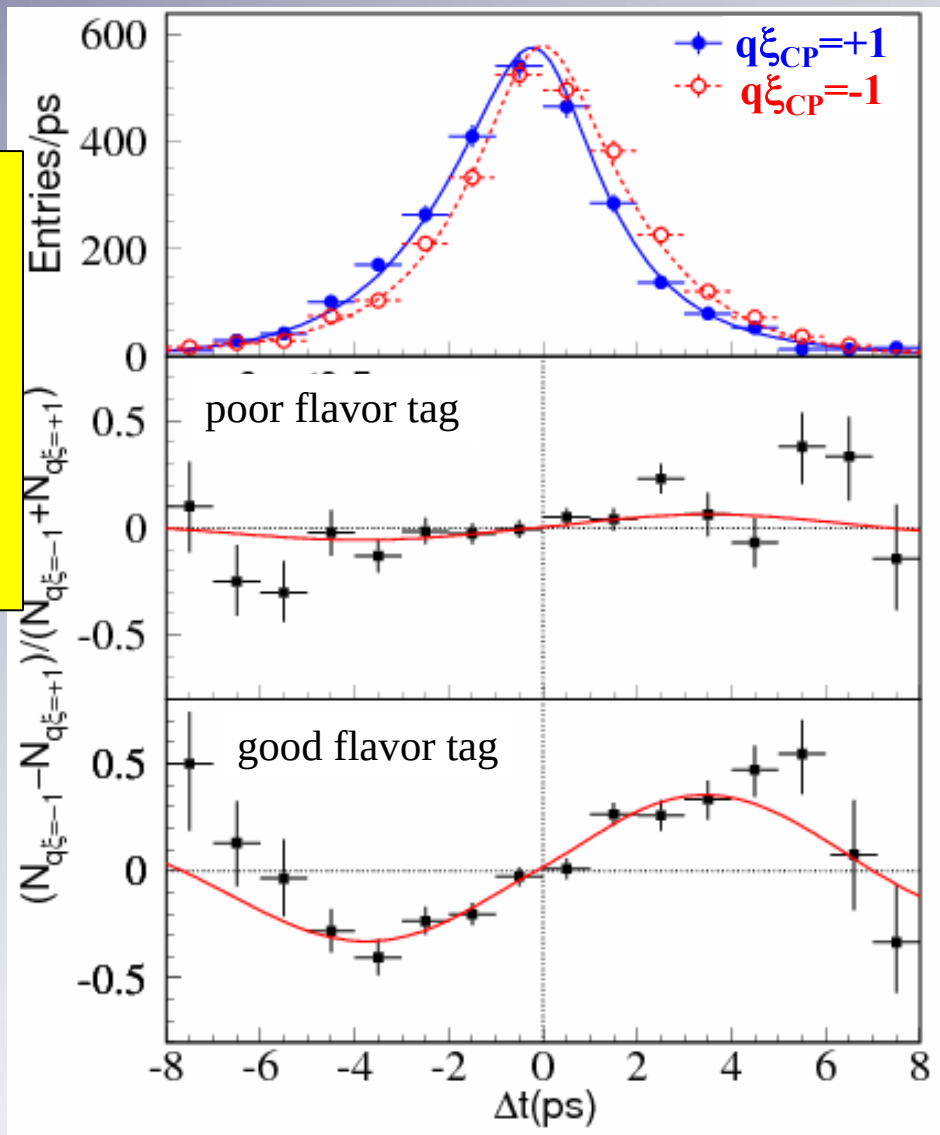
$\sin 2\phi_1 = 0.728 \pm 0.056$ (stat) ± 0.023 (syst)

$|\lambda_{CP}| = 1.007 \pm 0.041$ (stat) ± 0.023 (syst)

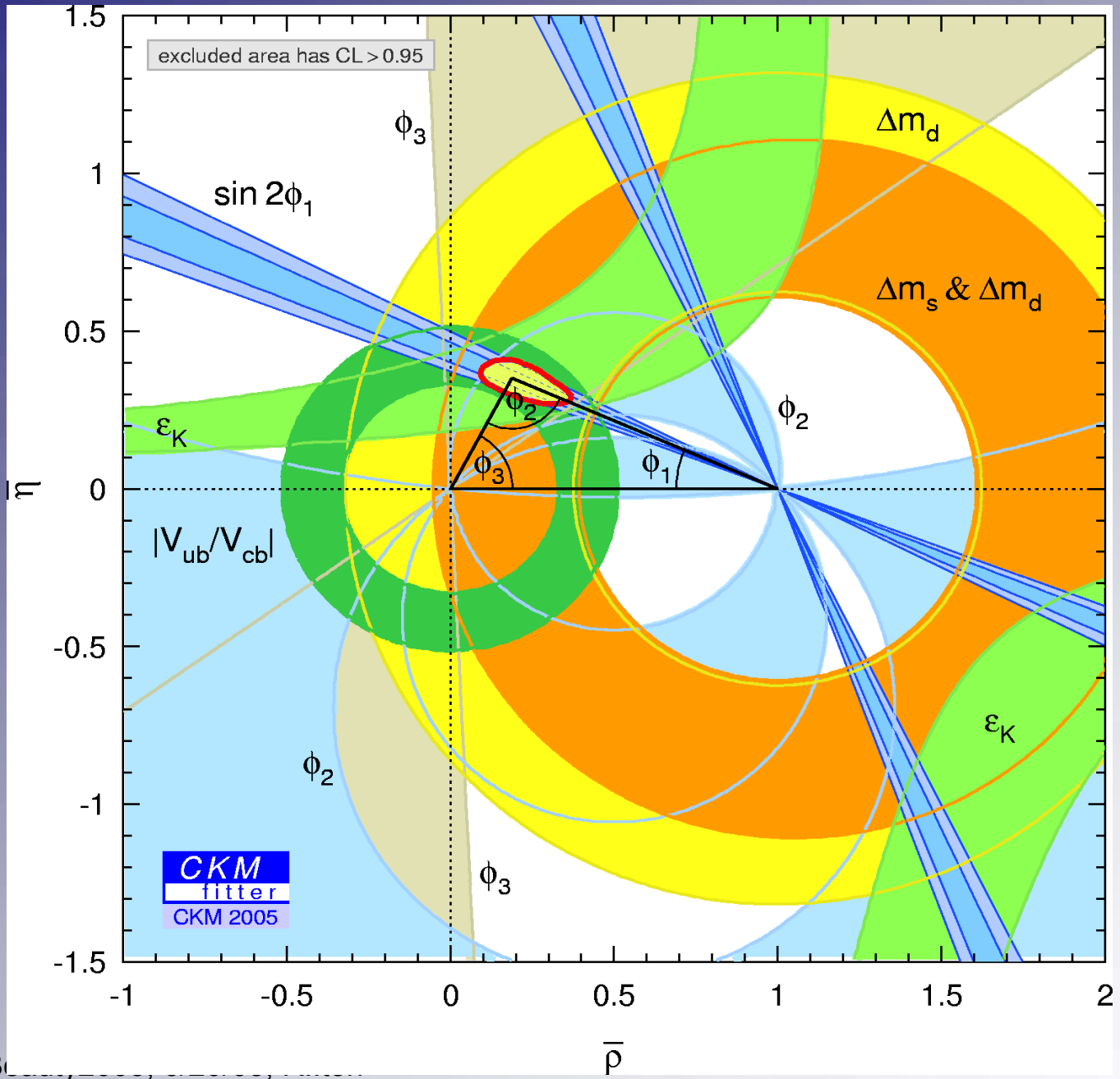
consistent with no-DCPV $|\lambda_{CP}|=1 \Leftrightarrow A=0$

J/ψ Ks only (253/fb)

$\sin 2\phi_1(J/\psi K_s)=0.666\pm0.046$



Constraint on Unitarity Triangle (Belle+BaBar, as of CKM2005)



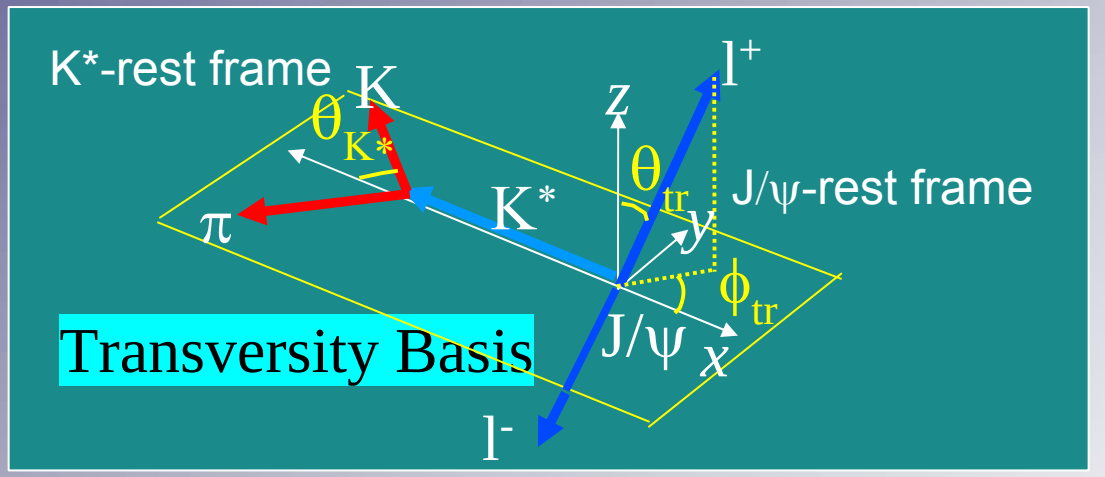
* Ambiguity in ϕ_1 from sin2ϕ_1 value:
  sin2ϕ_1 = 0.726
  → ϕ_1 = 23.3° or 66.6°

* Measurement of cos2ϕ_1 can resolve the two-fold ambiguity

Resolving ϕ_1 ambiguity : $B^0 \to J/\psi K^*$ decays

hep-ex/0504030 (PRL)

* Time-dependent full angular analysis for decay products of $B^0 \to J/\psi(l^+l^-)K^*(K_s\pi^0)$



$$\frac{1}{d\Gamma}\frac{d\Gamma}{d\cos\theta_{tr}\,d\phi\,d\cos\theta_{K^*}\,d\Delta t} = \frac{9}{32\pi}\frac{e^{-|\Delta t|}/\tau_B}{2\tau_B}\sum_{i=1,6} f_i(\theta_{tr},\phi,\theta_{K^*})\,a_i(\Delta t)$$

$$f_1 = 2\cos^2\theta_{K^*}(1-\sin^2\theta_{tr}\cos^2\phi)$$
$$f_2 = \sin^2\theta_{K^*}(1-\sin^2\theta_{tr}\sin^2\phi)$$
$$f_3 = \sin^2\theta_{K^*}\sin^2\theta_{tr}$$
$$f_4 = \frac{-1}{\sqrt{2}}\,sin2\theta_{K^*}\sin^2\theta_{tr}\,sin2\phi$$
$$f_5 = \sin^2\theta_{K^*}\,sin2\theta_{tr}\sin\phi$$
$$f_6 = \frac{1}{\sqrt{2}}\,sin2\theta_{K^*}\,sin2\theta_{tr}\cos\phi$$

$$a_1 = |A_0|^2(1+\eta\,sin2\phi_1\sin\Delta m\Delta t)$$
$$a_2 = |A_{//}|^2(1+\eta\,sin2\phi_1\sin\Delta m\Delta t)$$
$$a_3 = |A_T|^2(1-\eta\,sin2\phi_1\sin\Delta m\Delta t)$$
$$a_4 = \Re(A_{//}^* A_0)(1+\eta\,sin2\phi_1\sin\Delta m\Delta t)$$
$$a_5 = \eta\,\Im(A_{//}^* A_T)\cos\Delta m\Delta t - \eta\,\Re(A_{//}^* A_T)\,cos2\phi_1\sin\Delta m\Delta t$$
$$a_6 = \eta\,\Im(A_0^* A_T)\cos\Delta m\Delta t - \eta\,\Re(A_0^* A_T)\,cos2\phi_1\sin\Delta m\Delta t$$

* A_0, $A_{//}$, A_T : decay amplitudes
* Δm, τ_B : mixing parameter, B lifetime
* η : +1 for B^0, -1 for $\overline{B^0}$
* ϕ_1 : CP violating angle (β)

Step 1: Measurement of decay amplitudes (253/fb)

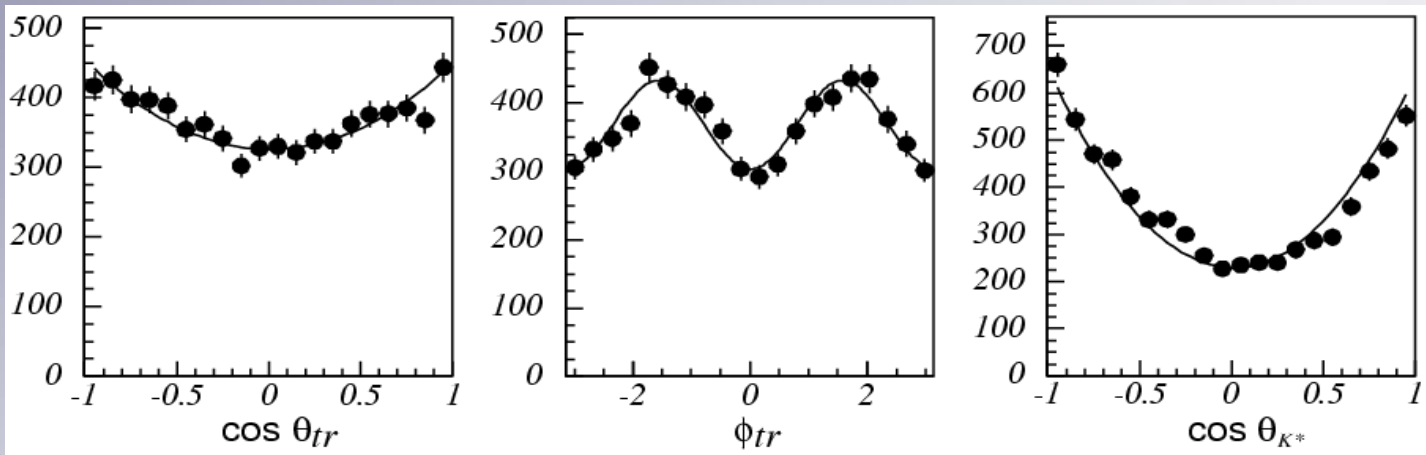
* Time-integrated angular analysis for $B^0 \to J/\psi K^*(K^+\pi^-)$

	B^0	$\overline{B}^0$	$B^0+\overline{B}^0$
$\|A_0\|^2$	0.571±0.015	0.578±0.016	0.574±0.012±0.009
$\|A_{//}\|^2$	0.216±0.017	0.244±0.018	0.231±0.012±0.008
$\|A_{\perp}\|^2$	0.213±0.017	0.178±0.017	0.195±0.012±0.008
$\arg(A_{//})$	-2.934±0.134	-2.851±0.114	-2.887±0.090±0.008
$\arg(A_{\perp})$	2.878±0.088	2.993±0.089	2.938±0.064±0.010

$\arg(A_0) = 0$ (def.) *Note: Phases are chosen to conserve s quark helicity*

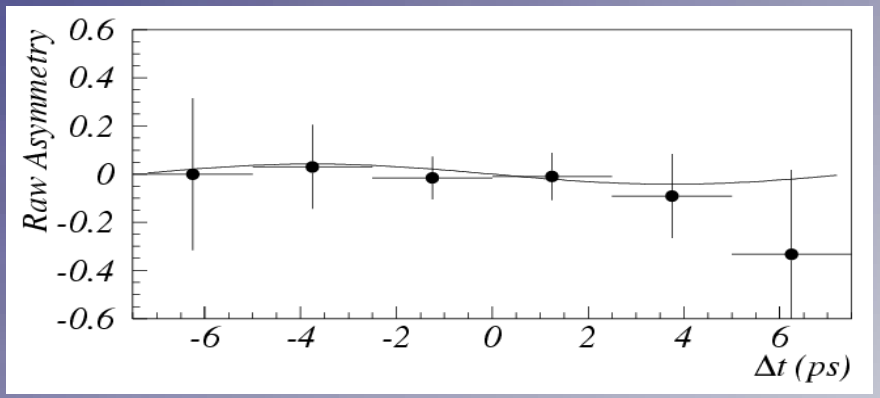
*** No direct CPV observed**

- Evidence of final state interactions in phases



Step2: Simultaneous determination of $\sin 2\phi_1$ and $\cos 2\phi_1$

- Fix decay amplitudes to measured values.
- Fit inputs : Δt, flavor, wrong tag fraction, ΔE, M_{bc} (standard CP fit)
  + three transversity angles
- Free parameters : $\sin 2\phi_1$, $\cos 2\phi_1$



(Sample : 363 events)

Results:

$\sin 2\phi_1 = 0.24 \pm 0.31 \pm 0.05$

$\cos 2\phi_1 = +0.56 \pm 0.79 \pm 0.11$

$+0.87 \pm 0.74 \pm 0.12$

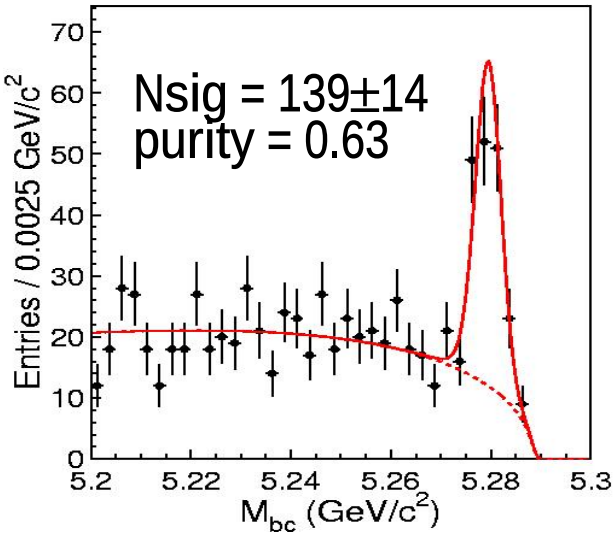
($\sin 2\phi_1$ is fixed at 0.726)

Consistent with a choice of $\phi_1 = 23.3^o$

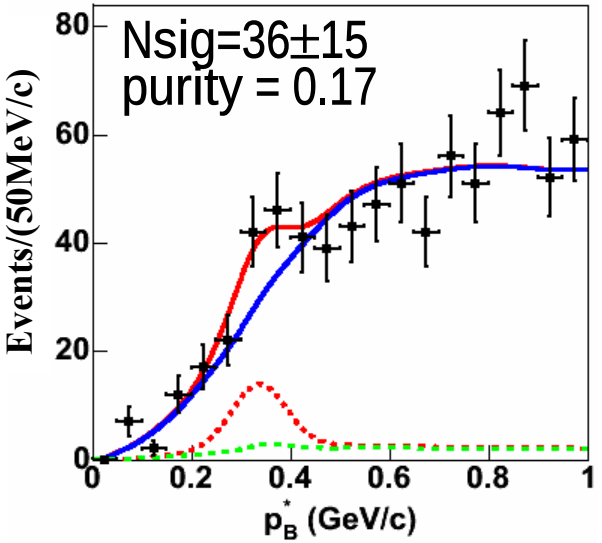
* Cannot exclude the other choice with a high confidence level.
  - Statistical error is still large (only ~2σ from the other choice).
  - Ambiguity in the choice of phases in decay amplitudes.
    ← study to resolve the ambiguity is now going on.

4. Measurement of ϕ_1 in b→s transition(253/fb)

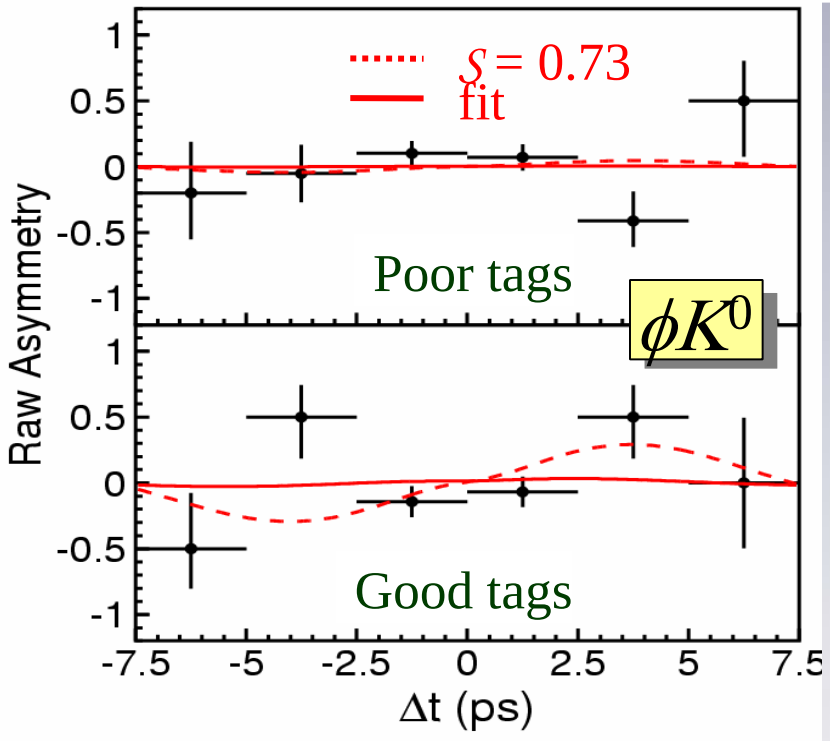
a) $B^0 \to \phi K^0$



φKs:
$\phi \to K^+K^-$
$Ks \to \pi^+\pi^-$, $\pi^0\pi^0$

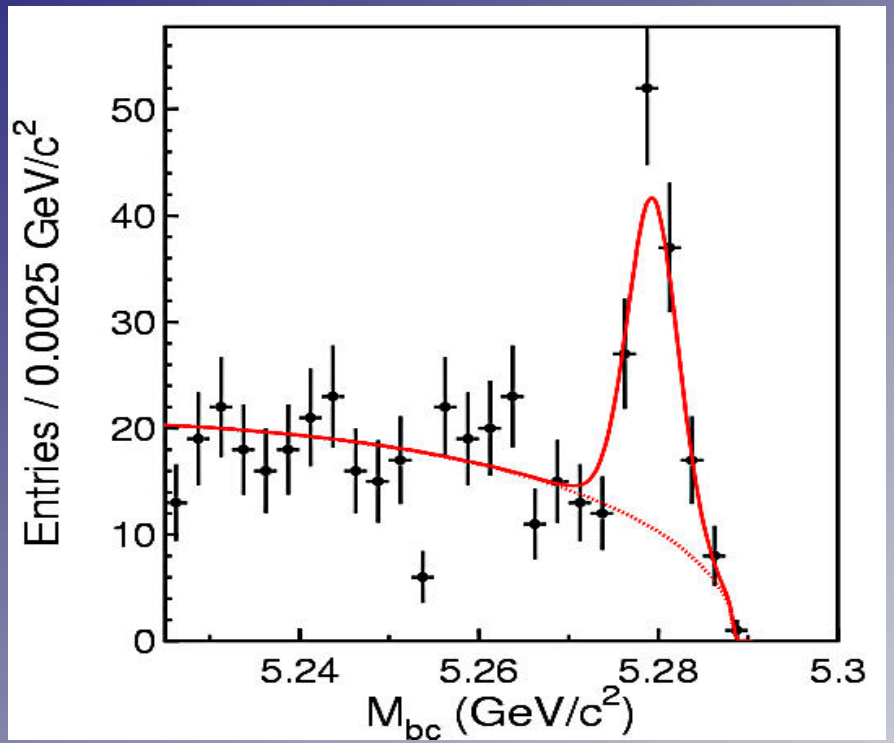


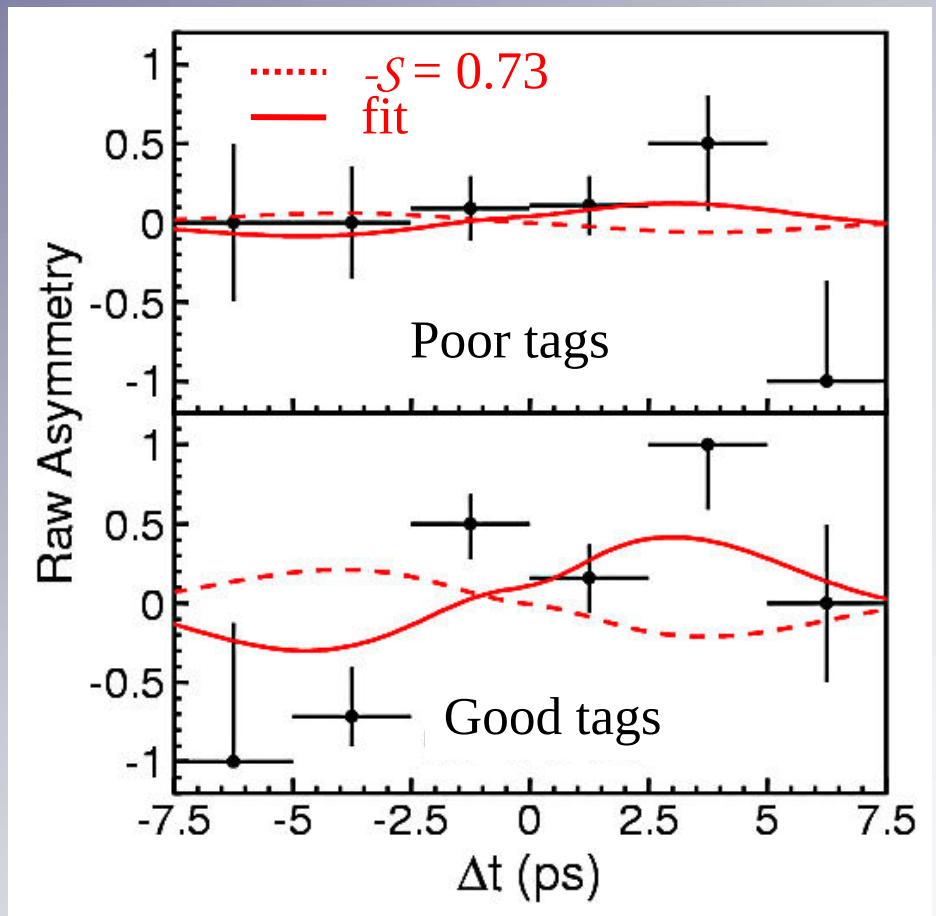
φK_L:
$\phi \to K^+K^-$
K_L w/
ECL or KLM



"sin2ϕ_1"= +0.06 ±0.33 ±0.09
A = +0.08 ±0.22 ±0.09

b) $B^0 \rightarrow KsKsKs$

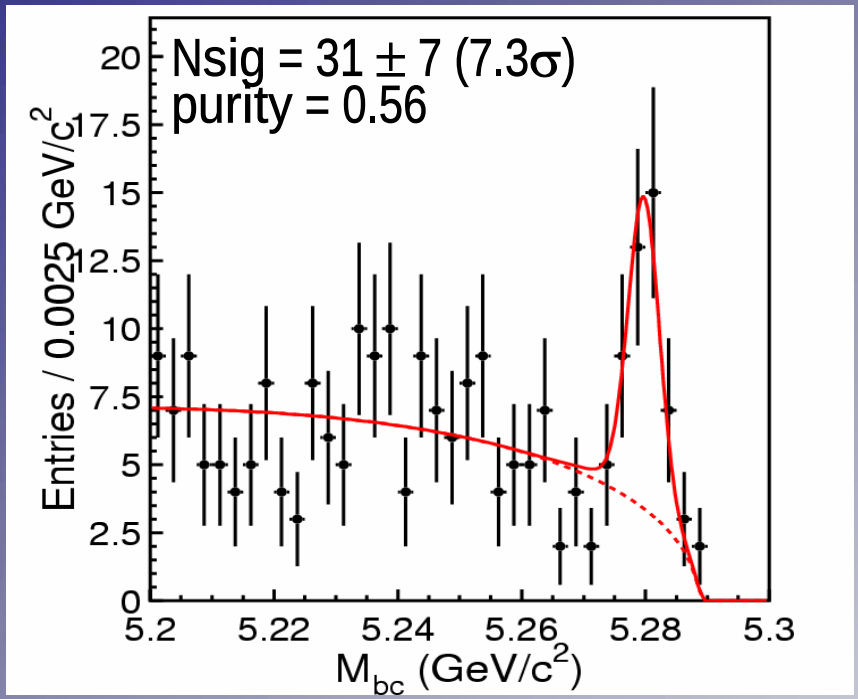


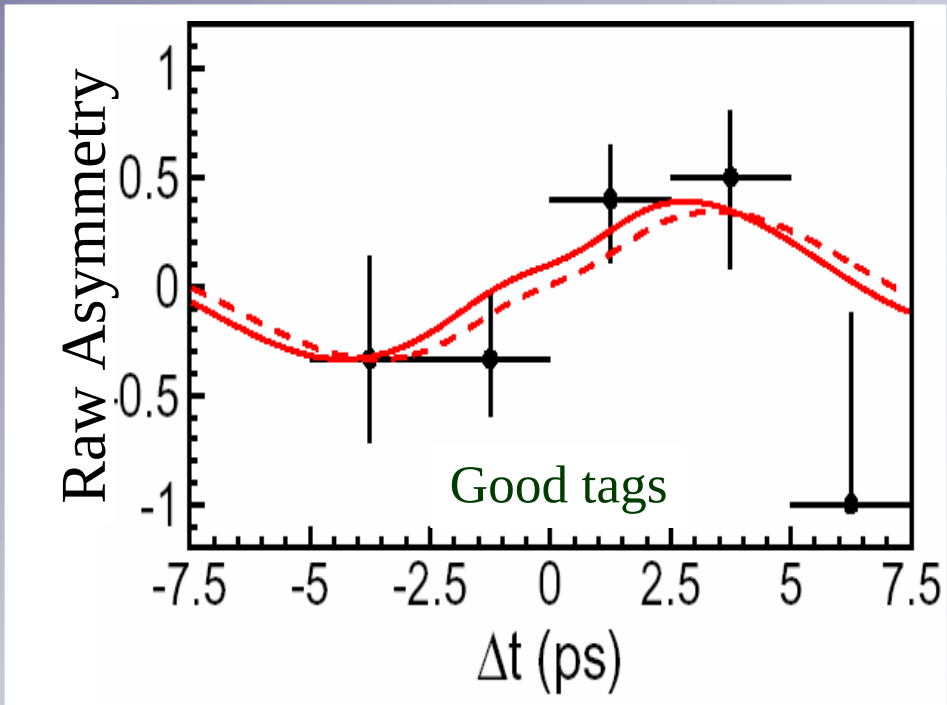


	w/ VTX	w/o VTX	total	N_{sig}
3 ($\pi^+\pi^-$)	96	32	128	72
2 ($\pi^+\pi^-$) & ($\pi^0\pi^0$)	21	18	39	16
total	117	50	167	88

"sin2ϕ_1"= –1.26 ±0.68 ±0.18
A = +0.54 ±0.34 ±0.08

c) $B^0 \to \omega K_S$

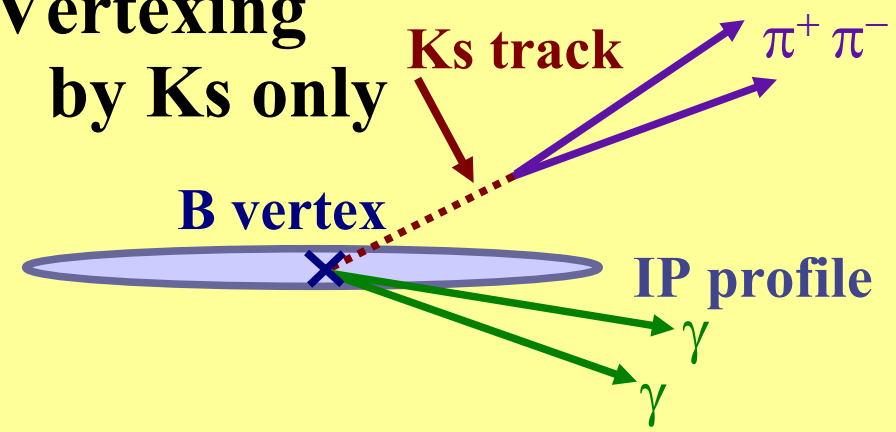




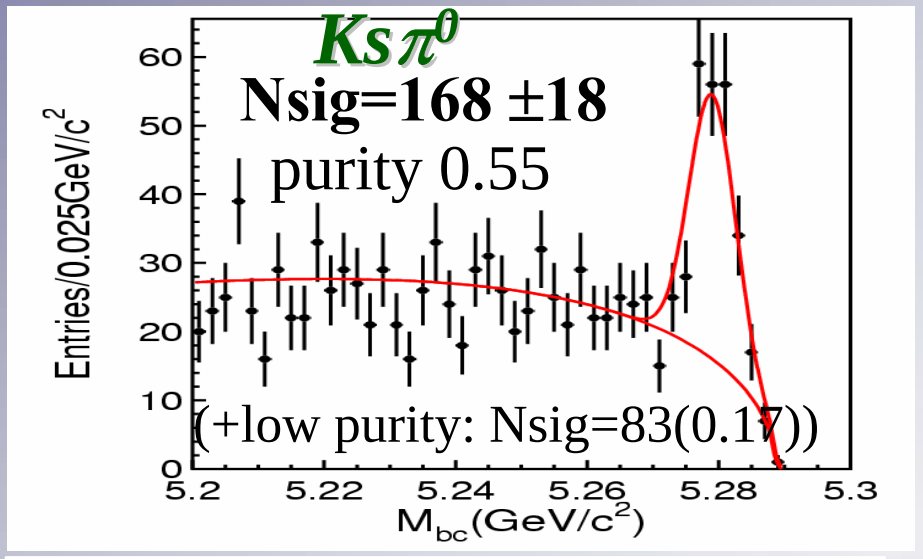
$$\text{“}\sin 2\phi_1\text{”} = +0.75 \pm 0.64\ ^{+0.13}_{-0.16}$$
$$A = +0.26 \pm 0.48 \pm 0.15$$

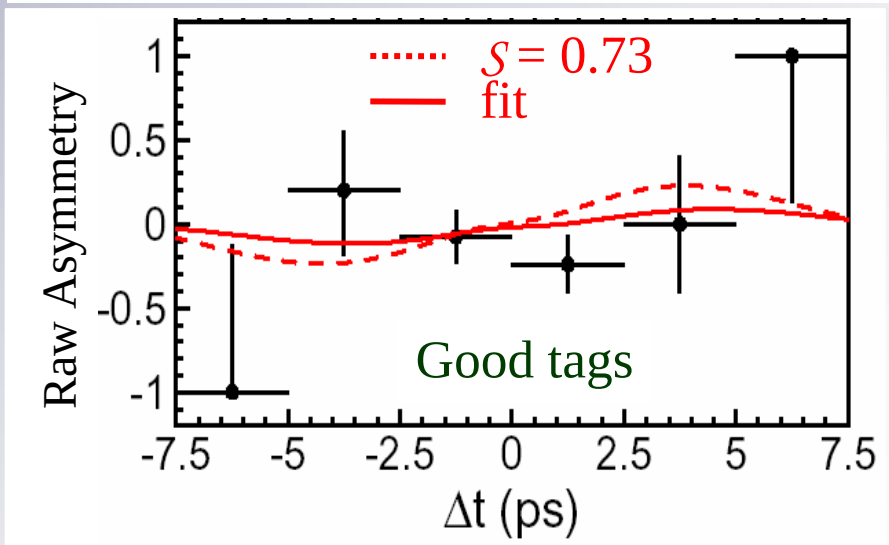
d) $B^0 \to K_s \pi^0$

Vertexing by Ks only



Validated by J/ψ Ks (use Ks only)

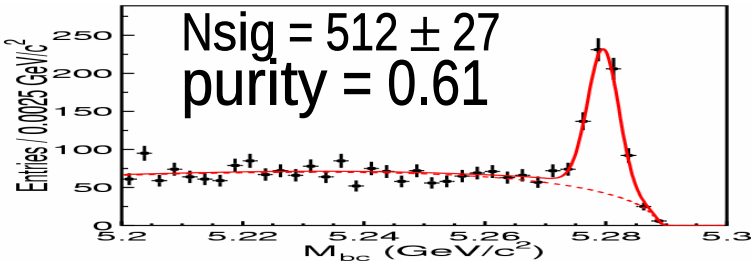


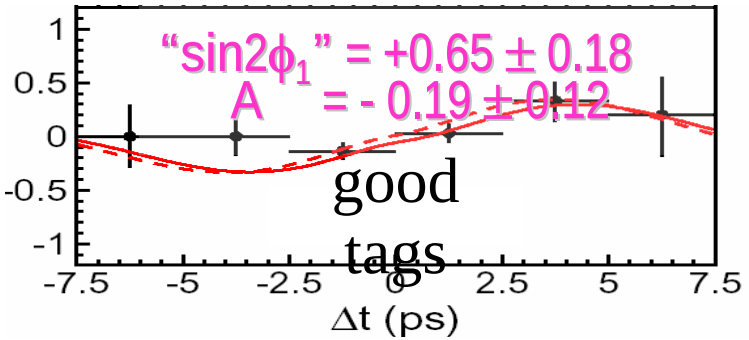


"sin2ϕ_1" = +0.30 ±0.59 ±0.11
A = –0.12 ±0.20 ±0.07

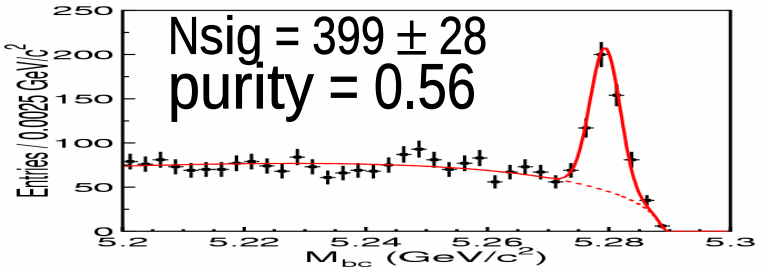
e) Other modes

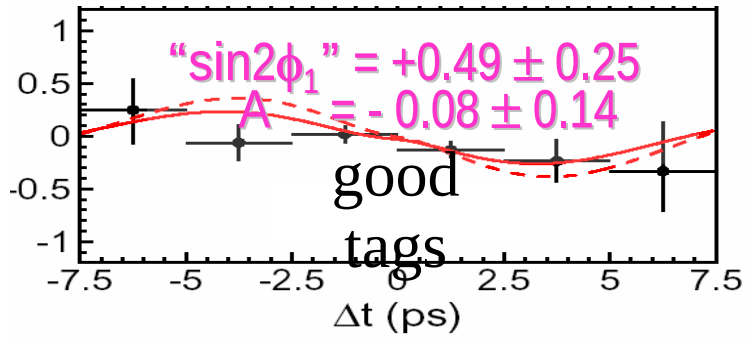
$\eta' K_S$



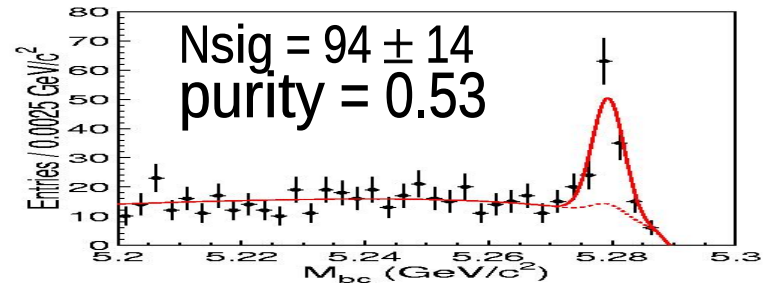


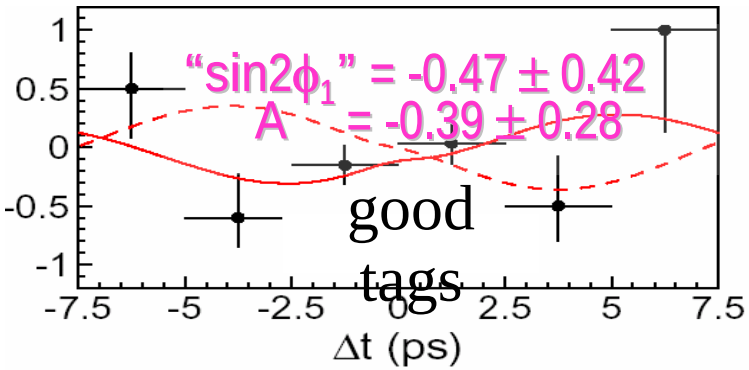
$K^+K^-K_S$



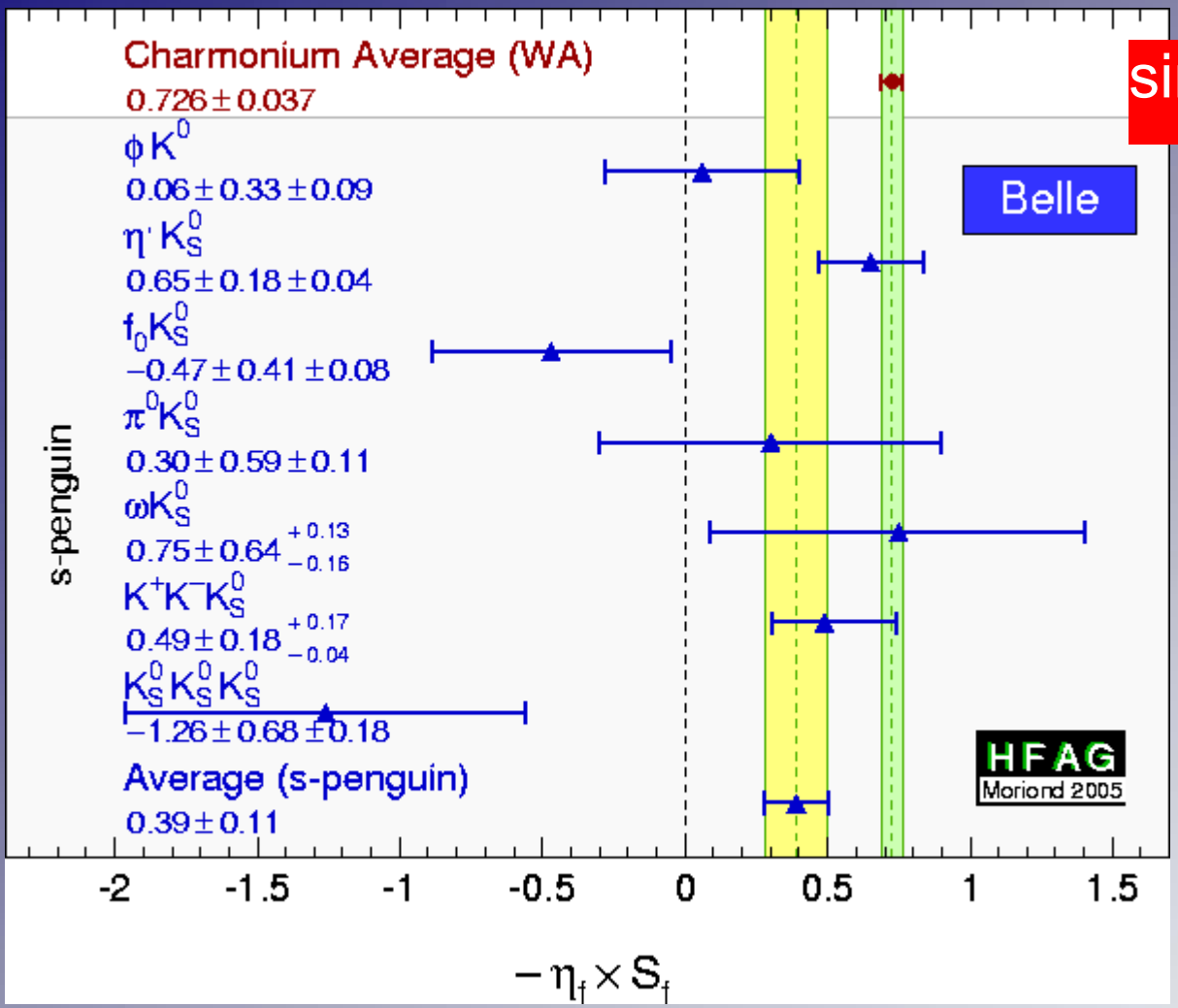


$f_0(980)K_S$





Summary of $\sin 2\phi_1^{eff}(b\to s)$ measured by Belle



$\sin 2\phi_1^{eff}(b\to s) = 0.39 \pm 0.11$ (ave.)

(with 253/fb)

→will be updated at LP05 with 350/fb

- $\sin 2\phi_1(b\to c) \leftrightarrow \sin 2\phi_1(b\to s)$ ~ 2.4 σ difference
- Averaged with BaBar's measurements ~3.8σ difference

New Physics?????

- Need more statistics (O(100) times) to confirm the difference
  - * Measuremet by ϕK^0 only (theoretically clean)
- Possibility of small discrepancies within the SM framework
  - * Rescattering
  - * Contamination of $b\to u$ tree in some modes

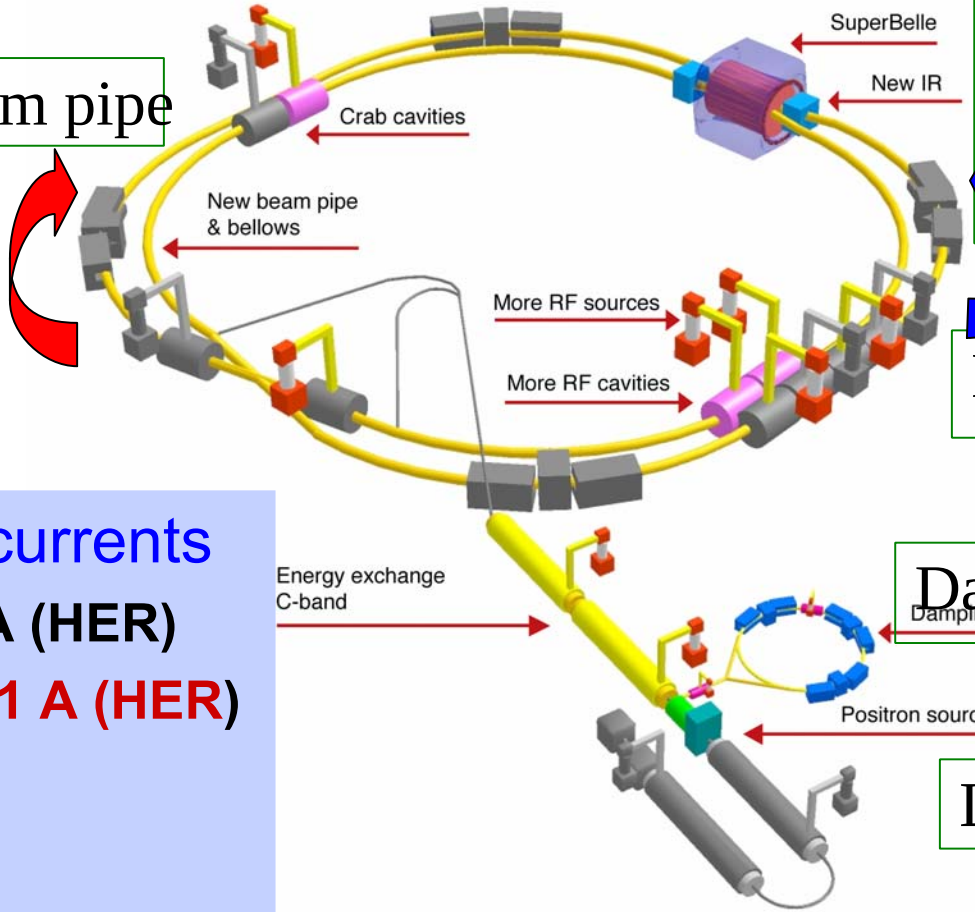
5. Future plan of ϕ_1 measurements

- Statistics! Statistics! Statistics! for more precise measurements
- Current luminosity ($1.5 \times 10^{34}/cm^2/sec$) is not enough to obtain required statistics in a reasonable time. **=> need ~ $5 \times 10^{35}/cm^2/sec$**

SuperKEKB

New Beam pipe

8GeV (e+, 4.1A)



Interaction Region

Crab crossing

θ=30mrad.

βy*=3mm

New QCS

3.5GeV (e-, 9.6A)

More RF power

Damping ring

Linac upgrade

Increase beam currents

- **1.6 A (LER) / 1.2 A (HER)**
  → **9.6 A (LER) / 4.1 A (HER)**

Smaller β_y^*

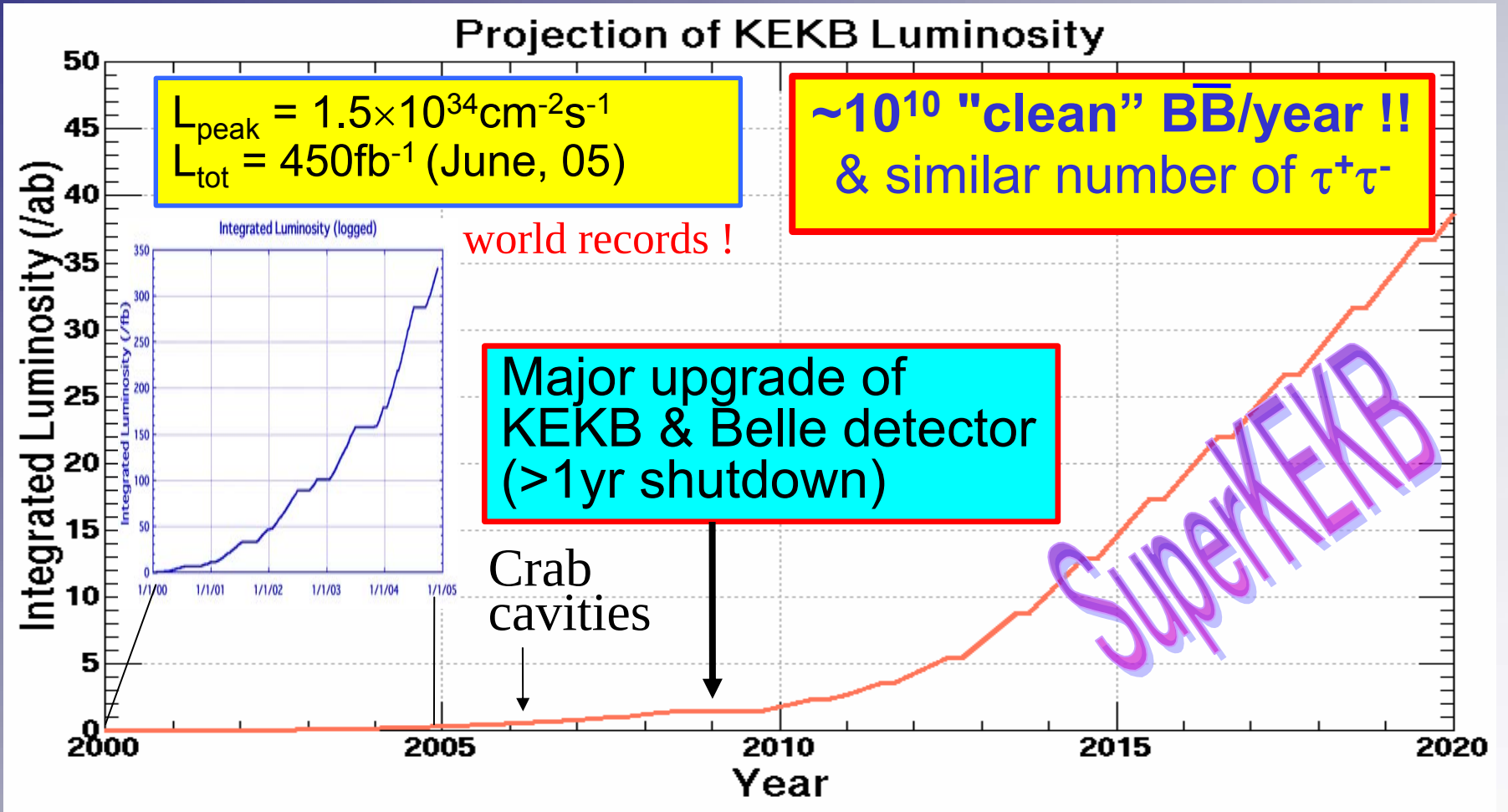
- **6 mm→3 mm**

Increase ξ_y

- **0.05→0.28(W-S)**

$L=3.5 \times 10^{35} cm^{-2} s^{-1}$

KEKB Upgrade Scenario

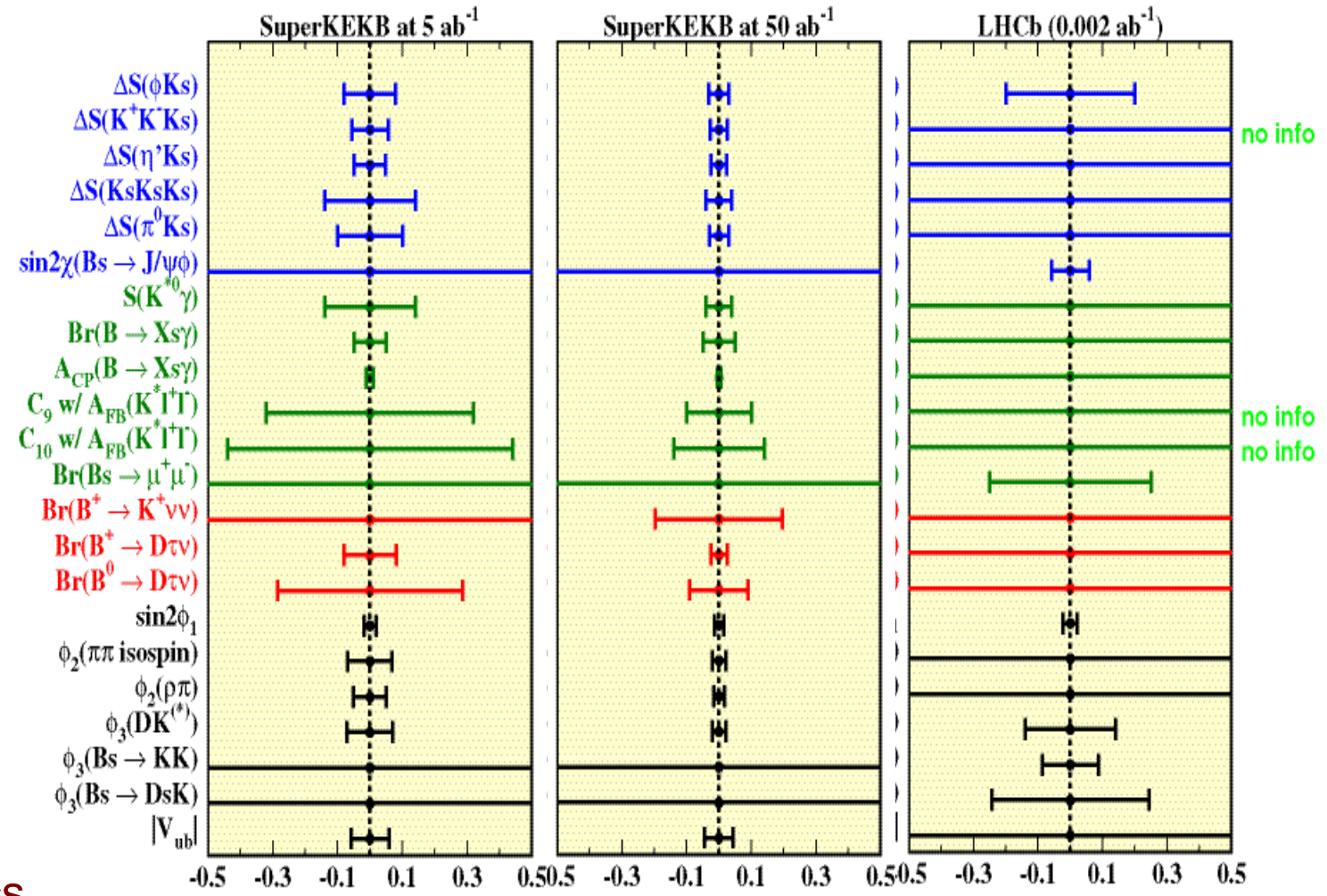


L_{peak} (cm^{-2}s^{-1})	1.5x10^{34}	5x10^{34}	5x10^{35}
L_{int}	450 fb^{-1}	~1 ab^{-1}	~10 ab^{-1}

Physics Reach at SuperKEKB

		SuperKEKB (5 ab^{-1})	(50 ab^{-1})
CPV (b→s)		0.079	0.031
		0.056	0.026
		0.049	0.024
		0.14	0.04
		0.10	0.03
		×	×
FCNC		0.14	0.04
		5%	5%
		0.011	5×10^{-3}
		32%	10%
		44%	14%
		×	×
w/ ν			5.1σ
		8%	2.5%
		3.5σ	9%
CKM		0.019	0.014
		3.9°	1.2°
		2.9°	0.9°
		4°	1.2°
		×	×
		×	×
		5.8%	4.4%

SuperKEKB 5ab^{-1} 50ab^{-1} LHCb 2fb^{-1}



and rich τ physics

SuperB↔LHCb
→ complementary

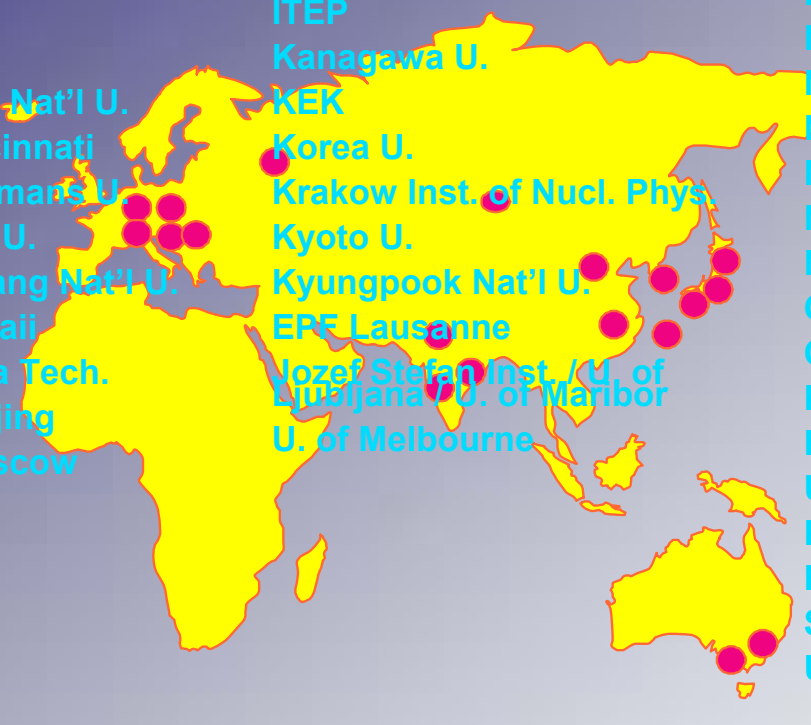
Physics at Super B Factory (hep-ex/0406071)

6. Summary

- The CP parameter $\sin 2\phi_1$ was measured by Belle for $b \to c$ and $b \to s$ transitions.
- The $\sin 2\phi_1$ value measured for $b \to c$ transition is
  $\sin 2\phi_1(b \to c) = \mathbf{0.728 \pm 0.056\ (stat) \pm 0.023\ (syst).}$
- Trying to resolve two-fold ambiguity in ϕ_1 from $\sin 2\phi_1$ using $B^0 \to J/\psi K^*$ decays. The result is consistent with the choice of $\phi_1 = 22.3^o$, however, the other choice cannot be excluded with present statistics.
- The average $\sin 2\phi_1$ value for $b \to s$ transition is
  $\sin 2\phi_1(b \to s) = \mathbf{0.39 \pm 0.11}$ (averaged by HFAG).
- More statistics is necessary to study the discrepancy.
  $\to$ SuperKEKB

Backup Slides

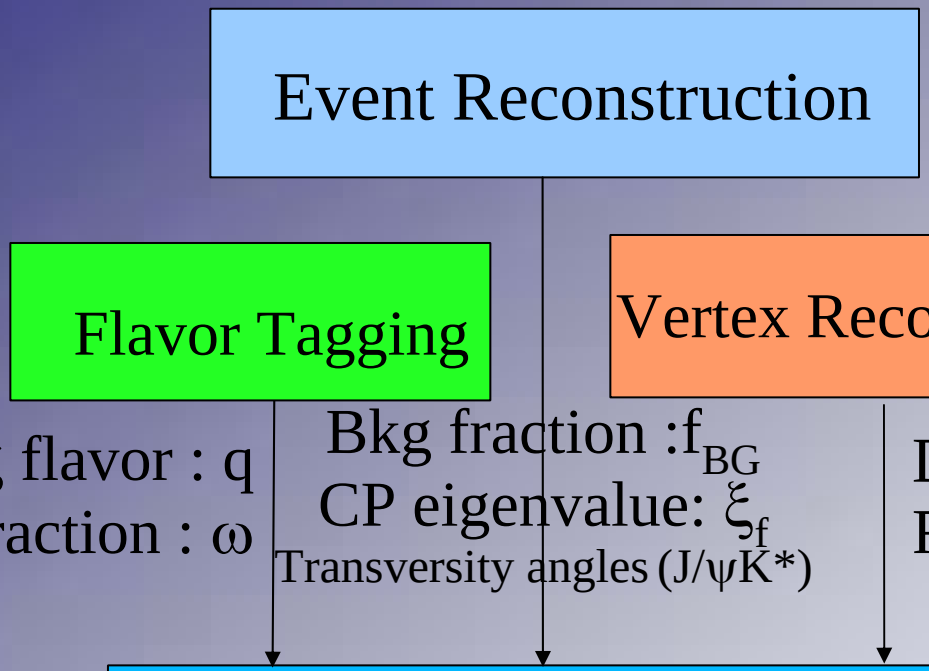
The *Belle* Collaboration



Aomori U.
BINP
Chiba U.
Chonnam Nat'l U.
U. of Cincinnati
Ewha Womans U.
Frankfurt U.
Gyeongsang Nat'l U.
U. of Hawaii
Hiroshima Tech.
IHEP, Beijing
IHEP, Moscow
IHEP, Vienna
ITEP
Kanagawa U.
KEK
Korea U.
Krakow Inst. of Nucl. Phys.
Kyoto U.
Kyungpook Nat'l U.
EPF Lausanne
Jozef Stefan Inst. / U. of Ljubljana / U. of Maribor
U. of Melbourne
Nagoya U.
Nara Women's U.
National Central U.
Nat'l Kaoshiung Normal U.
National Taiwan U.
National United U.
Nihon Dental College
Niigata U.
Osaka U.
Osaka City U.
Panjab U.
Peking U.
U. of Pittsburgh
Princeton U.
Riken
Saga U.
USTC
Seoul National U.
Shinshu U.
Sungkyunkwan U.
U. of Sydney
Tata Institute
Toho U.
Tohoku U.
Tohuku Gakuin U.
U. of Tokyo
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
Toyama Nat'l College
U. of Tsukuba
Utkal U.
VPI
Yonsei U.

13 countries, 57 institutes, ~400 members

Procedure of CP fitting



$$L_i = (1 - f_{ol})\left[f_{sig} \cdot P_{sig} \otimes R_{sig} + (1 - f_{sig}) \cdot P_{bkg} \otimes R_{bkg} \right] + f_{ol} \cdot P_{ol}$$

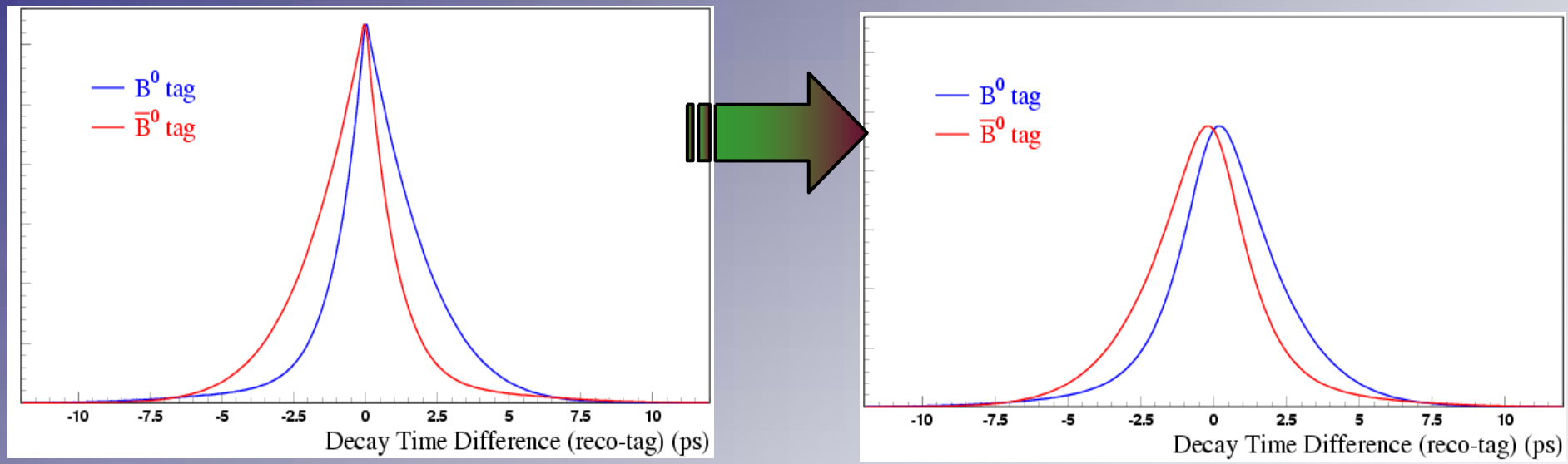
$$P_{sig}(\Delta t; S, A, q, w, \Delta w) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 - q \cdot \Delta w + q(1 - 2w)\{S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)\}\right]$$

Free parameters

Tagging and Δt resolution parameters

perfect
tagging & time resolution

observed
mistagging & finite time resolution



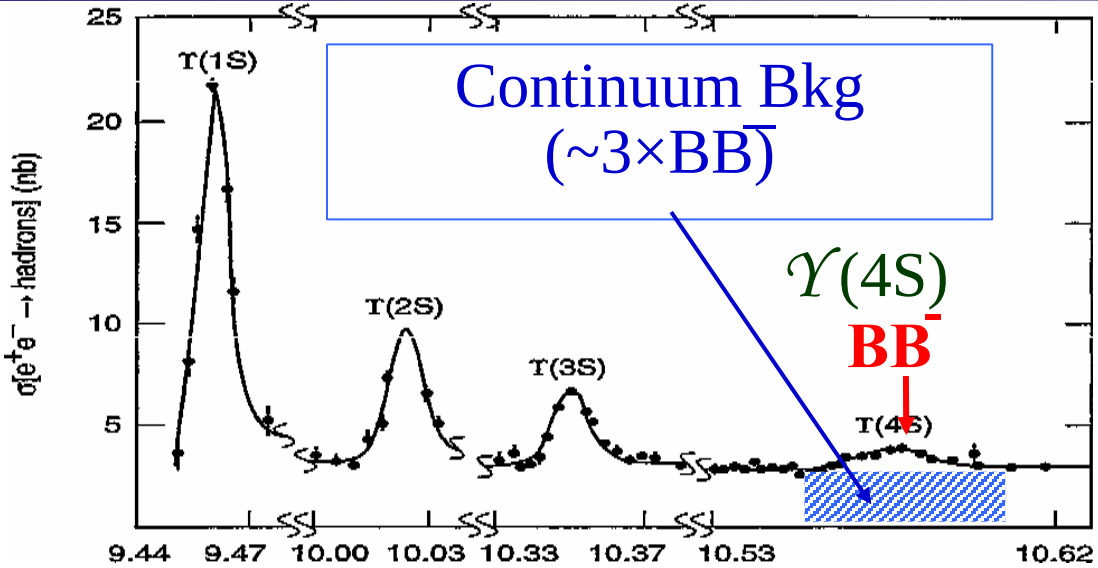
$$f(\Delta t) = \left[\frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left\{ 1 \mp (1-2w) S_{f_{cp}} \sin(\Delta m \Delta t) \right\} \right] \otimes R$$

Wrong tagging fraction

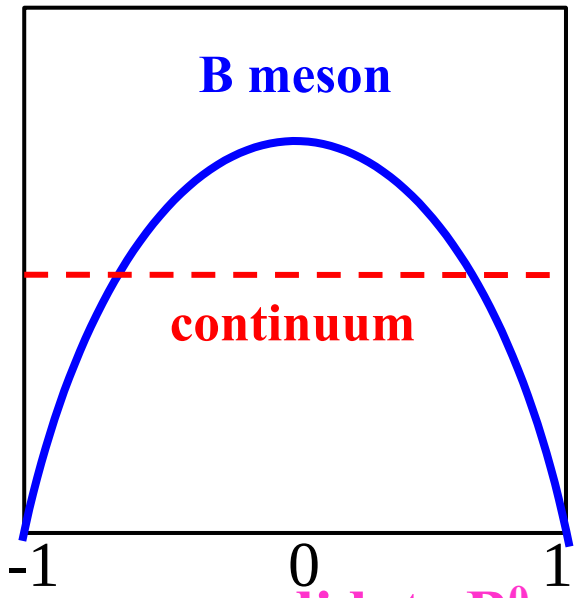
Resolution function

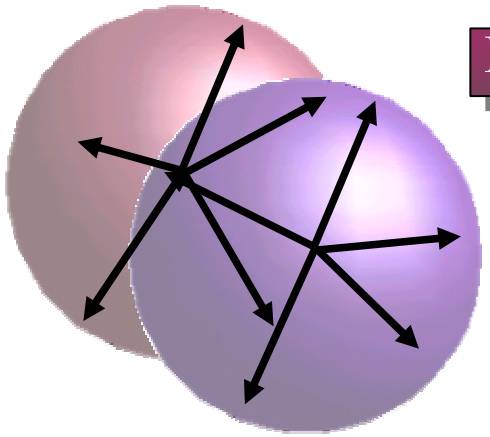
R and w are determined from data using flavor specific decays
$B \rightarrow D^{(*)-} \pi^+, \rho^+, a_1^+$ and $J/\Psi K^{*0}$ …

Continuum Background Suppression

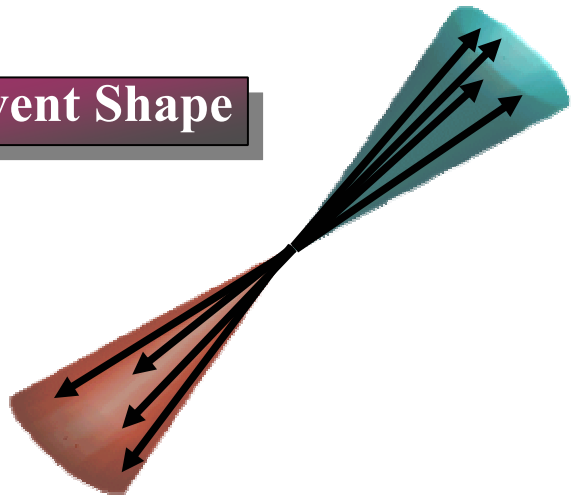


Br(b→s) = 10^{-5} ~10^{-6}
for each modes





Event Shape

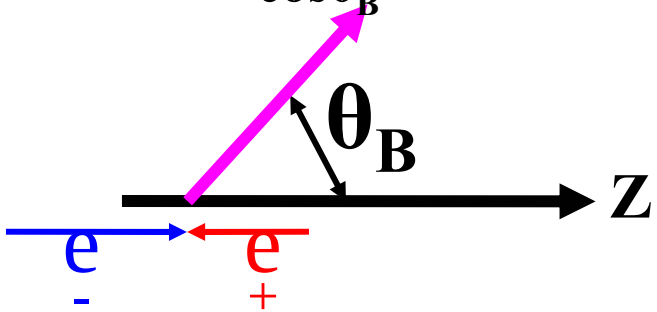


$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

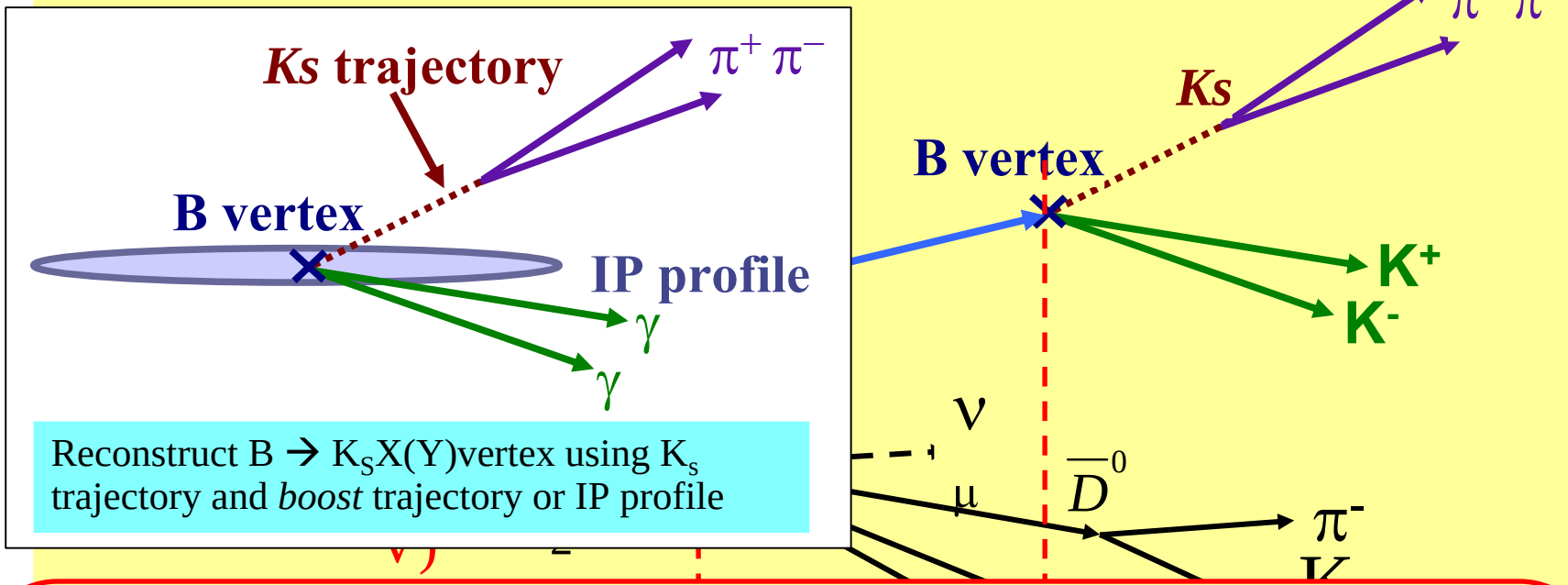
(Spherical)

$e^+e^- \to q\bar{q}$

(Jet-like)

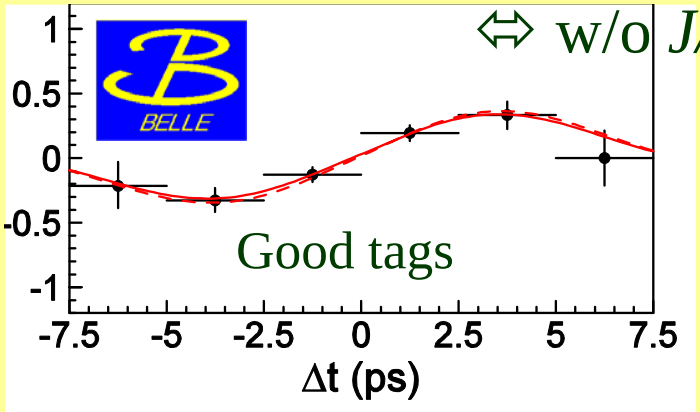


Vertex reconstruction w/ K_S trajectory



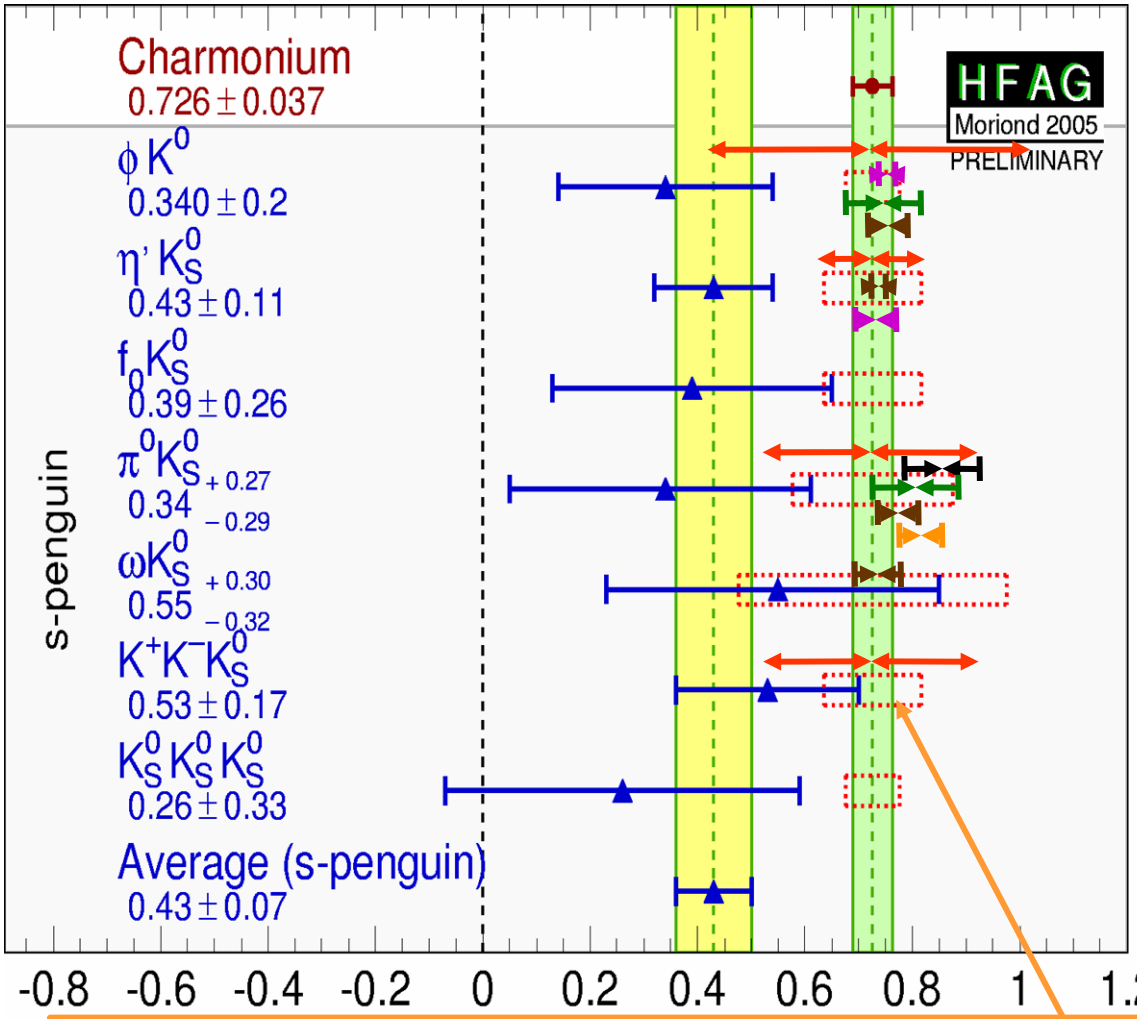
Reconstruct B → K_SX(Y)vertex using K_s trajectory and *boost* trajectory or IP profile

Validated with J/ΨKs: w/ K_S vtx ⇔ w/o J/Ψ vtx



	w/ J/Ψ	w/ K_S
S	+0.65 ±0.05	+0.68 ±0.10
A	+0.01 ±0.04	+0.02 ±0.04

Theoretical uncertainties of "sin2ϕ_1"



also shown: naive upper limit based on final state quark content, CKM (λ^2) and loop/tree (= 0.2-0.3) suppression factors
[Kirkby,Nir, Phys. Lett. B592 (PDG review);Hoecker, hep-ex/0410069]

- amount of possible discrepancies $\Delta\sin2\beta$ have been evaluated for some modes:
  - model independent upper limits based on SU(3) flavor symmetry and measured ***b d,sqq*** B.R.

    2x$\Delta\sin2\beta$

    - *[Grossman et al,Phys Rev D58; Grossman et al., Phys Rev D68; Gronau, Rosner, Phys.Lett. B564; Gronau et al., Phys.Lett.B579; Gronau, at al. Phys.Lett.B596; Chiang at al., Phys.Rev.D70]*
  - estimates of deviations based on QCD-motivated specific models; some have difficulties to reconcile with measured B.R. (errors summed in quadrature)
    - *Beneke at al., NPB675*
    - *Ciuchini at al., hep-ph/0407073*
    - *Cheng et al hep-ph/0502235*
    - *Buras et al. NPB697*
    - *Charles et al hep-ph/0406184*

Taken from talk slides by M.Morandin(INFN/Padoba) shown at Moriond EW (2005).

$\phi K_S/K_L$ Results

ϕK_S only

$\mathcal{S} = 0.00 \pm 0.33$
$\mathcal{A} = 0.06 \pm 0.22$

ϕK_L only

$-\mathcal{S} = 2.3 \pm 2.0$
$\mathcal{A} = 0.6 \pm 1.2$

CP component in $B \to K^+K^-K^0_S$ decay

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

$$|K^0\overline{K}^0\rangle = \frac{\alpha}{\sqrt{2}}(|K_SK_S\rangle + |K_LK_L\rangle) + \beta|K_SK_L\rangle$$

$CP = +1$ CP = even CP = odd

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

Using isospin symmetry,

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

$$\begin{aligned}\alpha^2 &= 2\frac{\mathcal{B}(B^+ \to K^+K_SK_S)}{\mathcal{B}(B^0 \to K^0K^+K^-)} \times \frac{\tau_{B^0}}{\tau_{B^+}} \\ &= \frac{\mathcal{B}(B^+ \to K^+K_SK_S)}{\mathcal{B}(B^0 \to K_SK^+K^-)} \times \frac{\tau_{B^0}}{\tau_{B^+}} \\ &= 1.03 \pm 0.15(\text{stat}) \pm 0.05(\text{syst})\end{aligned}$$

Systematic errors on $\mathcal{S}$

	Ks π^0	K*γ	ω Ks	η' Ks	f_0 Ks	ϕ K^0	K^+K^- Ks
VTX	0.02	0.06	0.01	0.01	0.02	0.01	0.01
flavor tag	0.01	0.02	0.04	0.01	0.01	0.01	<0.01
resolution	0.05	0.05	0.07	0.03	0.03	0.04	0.03
fit bias	0.03	0.03	+0.01 –0.10	0.01	0.03	0.01	0.01
signal fraction	0.07	0.02	0.10	0.02	0.05	+0.08 –0.06	0.02
physics parameters	0.02	0.01	0.01	<0.01	0.01	<0.01	<0.01
background Δt shape	0.04	0.03	0.02	<0.01	0.04	0.01	<0.01
tag side interference	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
TOTAL	0.11	0.10	+0.13 –0.16	0.04	0.08	0.09	0.04

KKK_S: effective $\sin 2\phi_1$ → 0.17 for CP-even fraction