Reflections on Beauty: CP Asymmetries at Belle

- CP violation in the Standard Model
- B(eauty) mesons & CP asymmetry
- B production: e^+e^- -> $\Upsilon(4S)$ at KEKB
- Belle experiment
  - Highlights in CP
  - Selected results
- Plans

Kay Kinoshita
University of Cincinnati
Belle Collaboration

Introduction: Particles & Interactions

Fundamental particles (relativistic QM)

- massless, relativistic QM states
- "discretely symmetric"

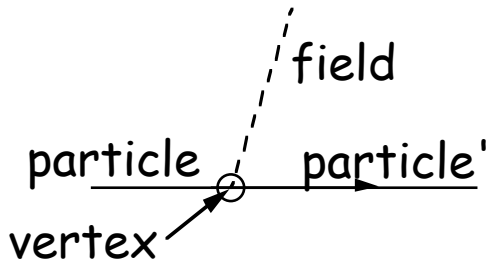
Parity	Time reversal	Charge conjugation
space	time	energy
r <-> -r	t <-> -t	f <-> anti-f

Universe

- massive particles (quarks, leptons)
- matter >> antimatter

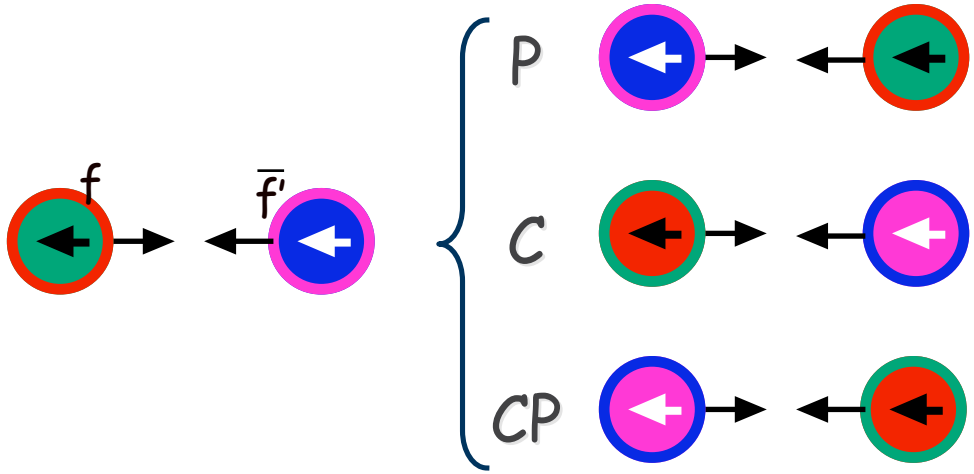
How can these be reconciled??

Forces (strong, EM, weak, gravitational)



- coupling strengths & symmetries -> mass, symmetries of cosmos
- matter-antimatter asymmetry requires CP-violating interactions (Sakharov 1967)

CP Violation: matter-antimatter asymmetry



Weak force:
P violated maximally
C "
CP conserved (mostly)

How can an interaction violate CP?

Complex coupling constant

$CP\{f \xrightarrow{g} f'\} = \bar{f}' \xrightarrow{g} \bar{f} \neq \bar{f}' \xrightarrow{g^*} \bar{f}$ (hermitian conjugate)

To be observable, need 2+ interfering amplitudes T,P:

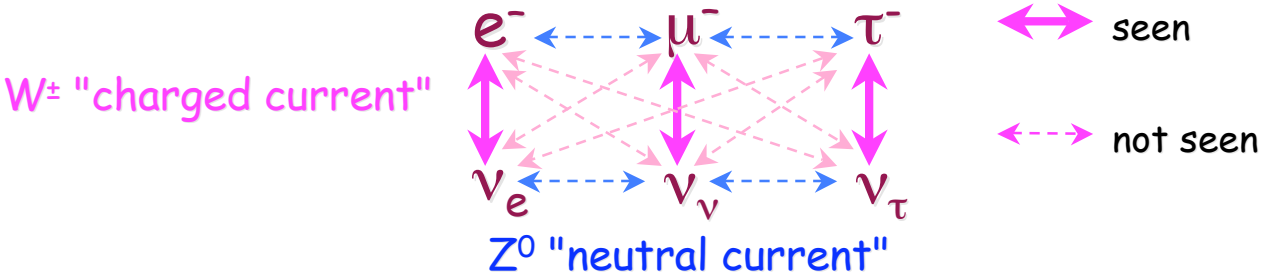
$T=gA, P=g'A' \rightarrow |gA+g'A'| \xrightarrow{CP} |gA^*+g'A'^*|$

Equal only if relative phase of g,g'=0

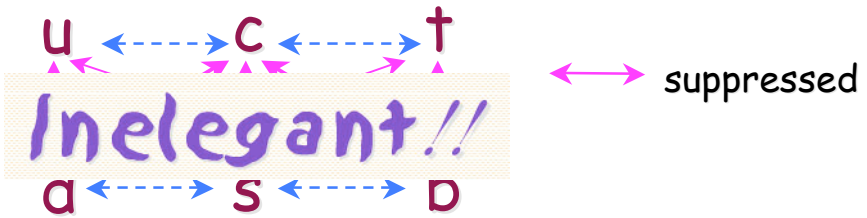
How does weak force violate CP?

Standard Model = 12 fermion flavors (+antifermion)

- 3 generations(distinguished only by mass)x2 typesx2 ea(strong & EM couplings) (stable, but for weak interaction)
- leptons: ~universal coupling, no generation x-ing



- quarks: neutral current – ~universal, no generation x-ing
- quarks: charged current – all different, approx. generation-conserving



Elegance restored: GIM mechanism

Picture

$$\{\text{matrix of couplings}\} = g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array}\!\!\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

can be expressed

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array}\!\!\begin{array}{c} \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

- d', s', b' are eigenstates resulting from perturbation by weak interaction.
  ≠ mass eigenstates d, s, b

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix

complex
preserves metric
" orthogonality
} ≡ unitary

Explains (Glashow-Iliopoulos-Maiani)

- suppression of flavor-changing neutral currents
- multiplicity of charged current couplings
- AND .....

… for >2 generations, e.g. **3**, {9$\mathcal{R}$+9$\mathcal{I}$} dof constrained by unitarity:

4 free parameters, incl. 1 irreducible **imaginary** part

>> *CP Violation* >> (Kobayashi-Maskawa 1973)

Makoto Kobayashi

First 3rd-generation particle (τ) seen 1975

Toshihide Maskawa

3-generation unitarity

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

irreducibly complex

from decay rates,

$\lambda = 0.220 \pm 0.002$

$A = 0.81 \pm 0.08$

$|\rho-i\eta| = 0.36 \pm 0.09$

$|1-\rho-i\eta| = 0.79 \pm 0.19$

Satisfies unitarity condition

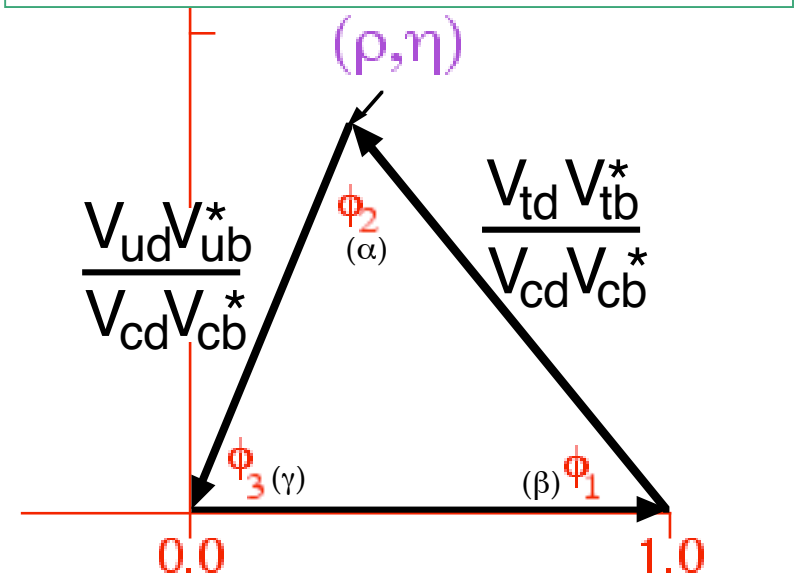
$$V_{ji}^* V_{jk} = \delta_{ik}$$

{i=1,k=3}: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

$$\Rightarrow \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$

$$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \rightarrow -(\rho+i\eta) \qquad \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} \rightarrow -(1-\rho-i\eta)$$

(ρ, η): "unitarity triangle"



Self-consistent if CKM is correct

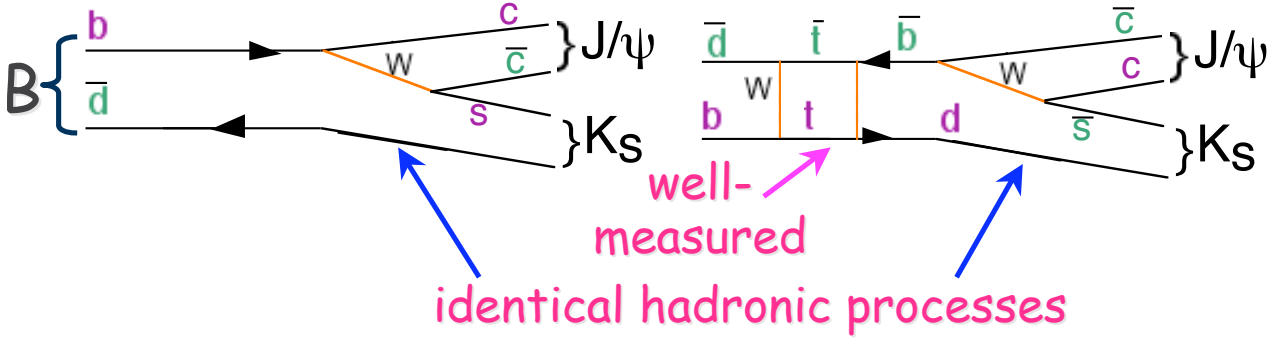
CP asymmetries with CKM

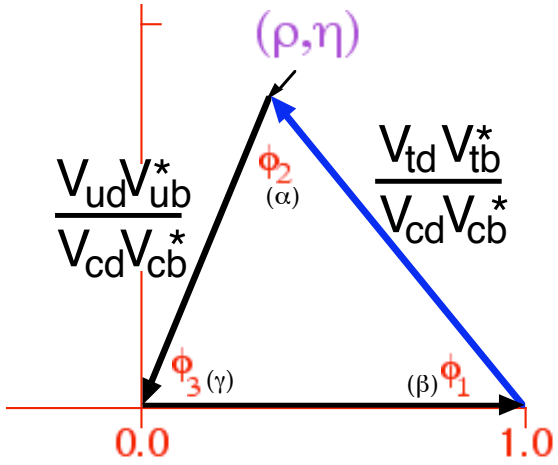
-> to observe, need process w. all 3 generations (<- B decays), interference between ≥2 processes

First goal: sin $2\phi_1$ in "golden mode" B -> J/ψ K_s (Sanda/Bigi/Carter)

tree (real V_{ij}) + mixing+tree ($\propto V_{td}^{*2}$)

$\propto V_{cb}^* V_{cs}$ $\propto V_{tb}^{*2} V_{td}^2 V_{cb} V_{cs}^*$





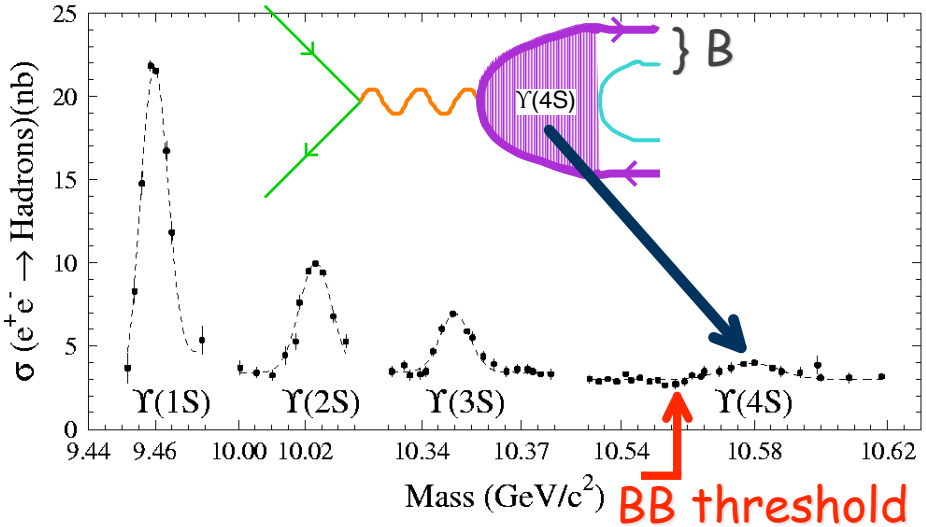
CP asymmetry from x-term(s) - no theoretical uncertainty: $\propto \arg(V_{td}^2) = 2\phi_1$

Bottom line: CP-dependent oscillation in time:

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b \eta_{CP} \sin 2\phi_1 \sin(\Delta m \Delta t));$$

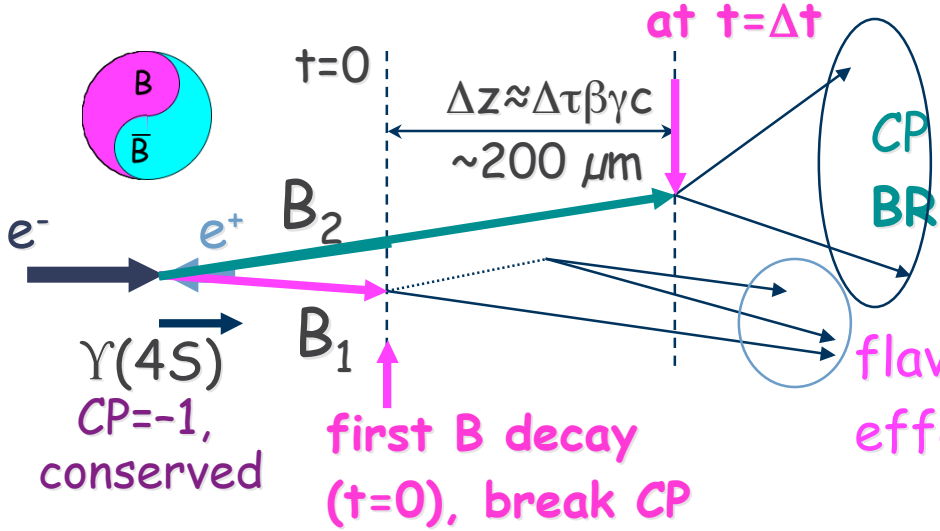
$$\eta_b = \begin{pmatrix} +1 \text{ if } B_{t=0} = B^0 \\ -1 \text{ if } B_{t=0} = \bar{B}^0 \end{pmatrix} \quad \eta_{CP} = \begin{pmatrix} -1 \text{ if } CP \text{ odd} \\ +1 \text{ if } CP \text{ even} \end{pmatrix}$$

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

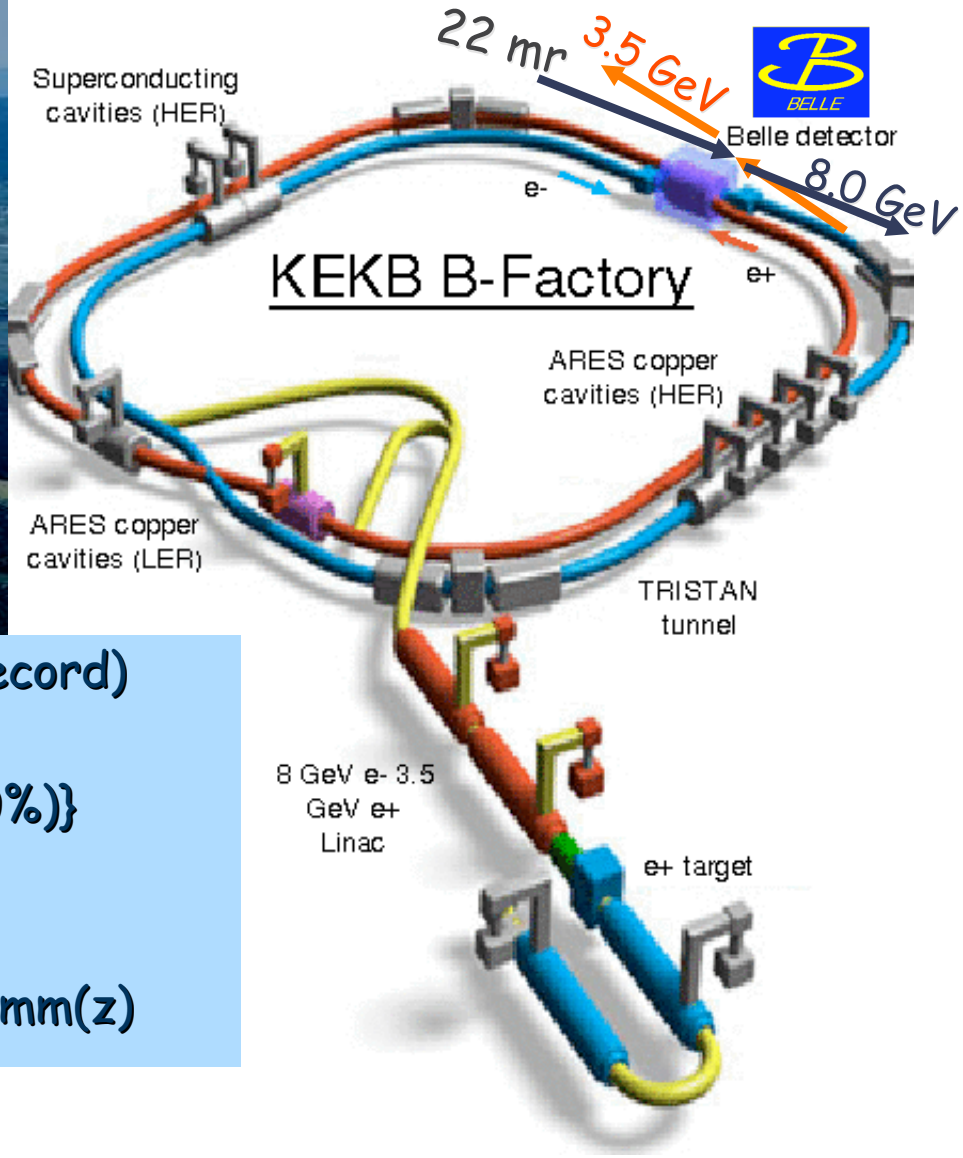


Δt by asymmetric energy e^+e^- -> Υ(4S)
(symmetric Υ(4S): CLEO 1979-2001)

Need
- hadron (K/π), lepton ID
- <<200μm vertexing
- statistics >>10^7 events



Colliding beams: KEKB



L_{max} = 1.40 X 10^{34} $cm^{-2}s^{-1}$ (world record)

Data (6/1999–1/2005)

$\int Ldt$ = 340 fb^{-1}@{Υ(4S)+off(~10%)}

(>3.5x10^8 B events)

$\sigma(E^*_{beam})$ = 2.6 MeV

IP size = 77μm(x) x 2.0μm(y) x 4.0mm(z)

The Detector

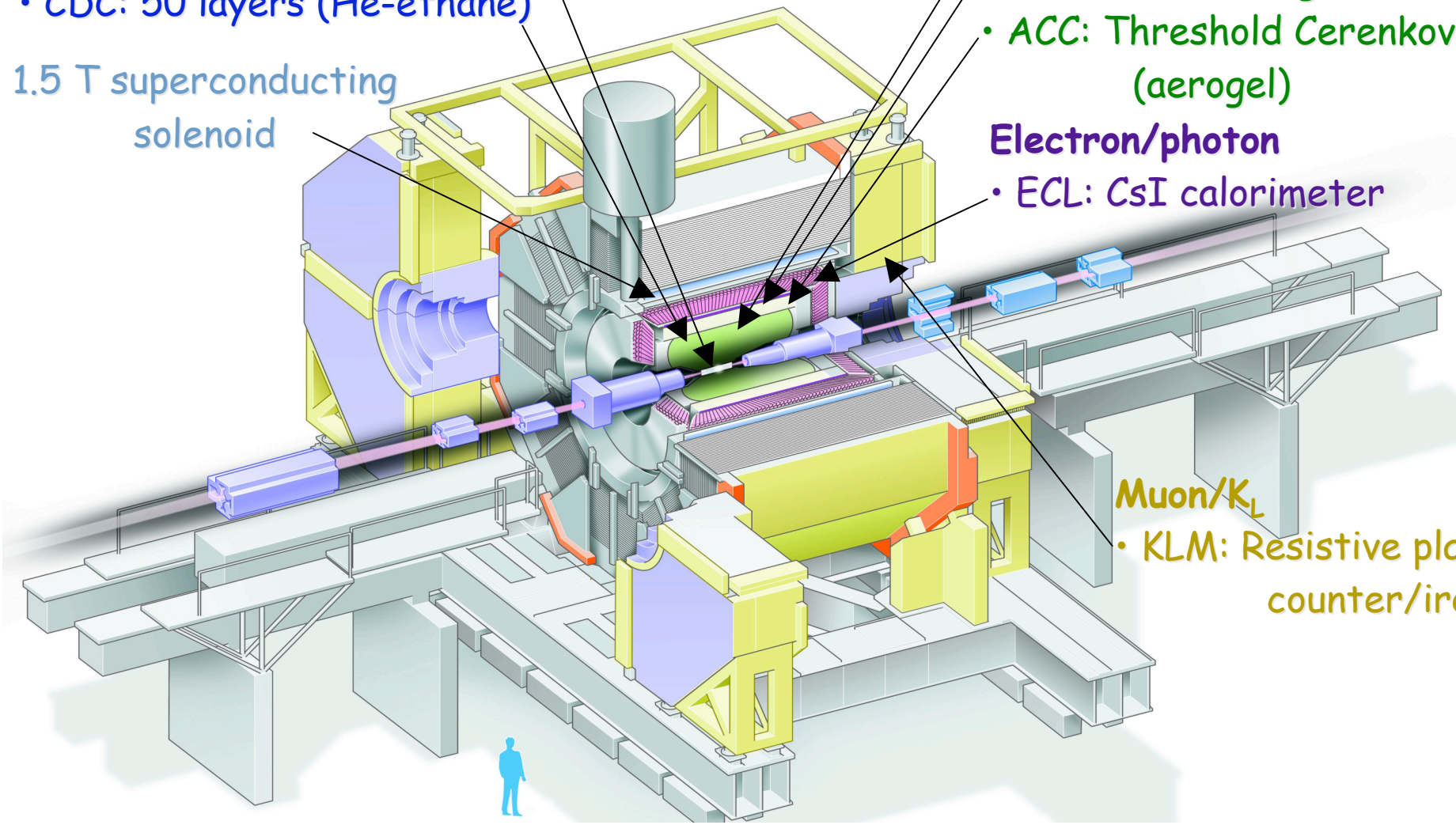
Charged tracking/vertexing
- SVD: 3-layer DSSD Si μstrip
- CDC: 50 layers (He-ethane)

1.5 T superconducting solenoid

Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

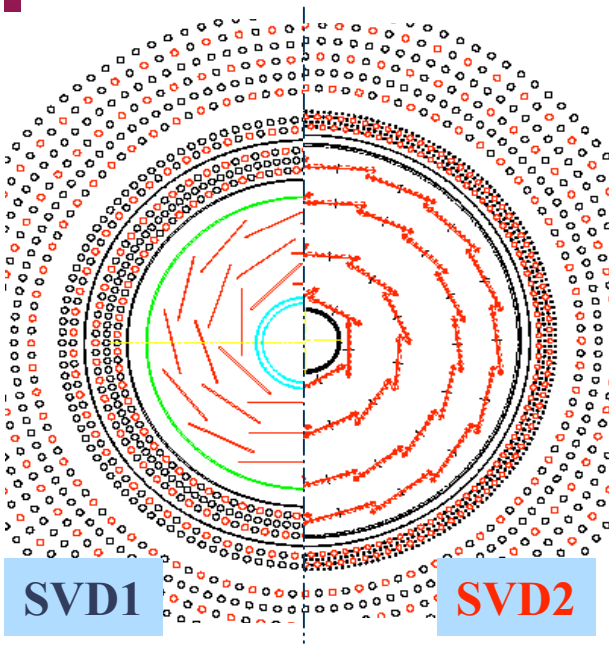
Electron/photon
- ECL: CsI calorimeter

Muon/K_L
- KLM: Resistive plate counter/iron

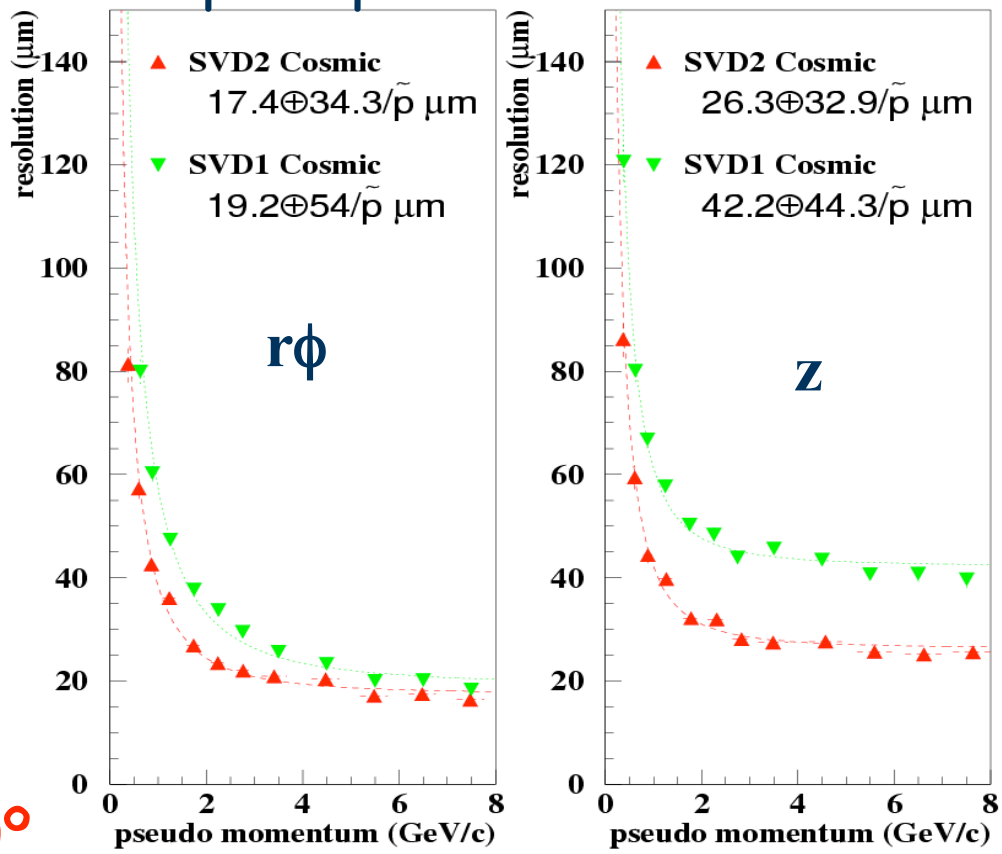


SVD Upgrade

2003 summer



Impact parameter resolution

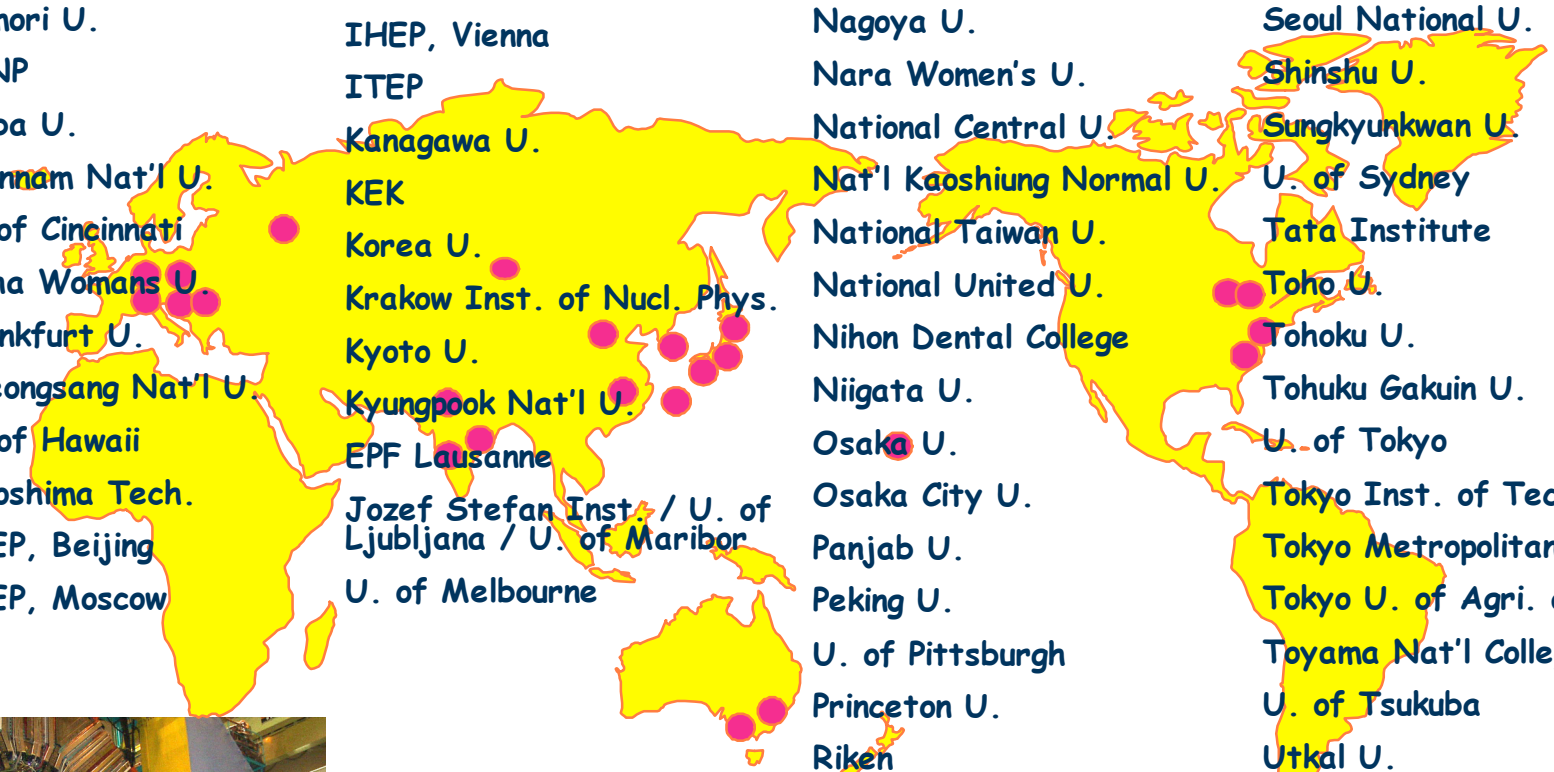


- 1 MRad → >20 MRad
- 3 layers → 4 layers
- $23° < \theta < 139°$ → $17° < \theta < 150°$
- R_{bp} = 2.0 cm → 1.5 cm

-> Better I.P. resolution

152M $B\bar{B}$ pairs w SVD1
+ 123M $B\bar{B}$ pairs w SVD2

… not least, the people



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.
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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 collaborators

(authors vary, each paper)

Belle physics

105±5 papers published or in press (#1 in 3/2001)

65 papers submitted to ICHEP 2004

(CP asymmetry in B decay, other B decay, charm, tau, 2-photon)

Physics topics overlap in many analyses,

e.g., discovery of new charmonium(-like) states in B decay.

Recent highlights in CP

B: CP and related

- time-dependent CP measurements

  updated $J/\psi K_S$,$J/\psi K_L$ (ϕ_1), ϕK_s(ϕ_1)

  + $J/\psi\pi^0$(~ϕ_1), $D^{*+}\pi^-$($2\phi_1+\phi_3$), $\pi^+\pi^-$,$\rho^+\pi^0$,$\rho^+\pi^-$(~ϕ_2), $K^-\pi^+$(ϕ_1),

    ηK^+, $\eta\pi^+$, ϕK_s,$\eta' K_s$, $f^0 K_s$,$\pi^0 K_s$, ωK_S,$K^+K^-K_s$,$K_sK_sK_s$ (ϕ_1)

- evidence/observation

  B-> $K^*l^+l^-$, $\pi^0\pi^0$, D^+D^-, $\pi^0\rho^0$, K^* ρ, ...

- method for ϕ_3: Dalitz plot analysis

  D^0K^+ {D^0->$K_s\pi^+\pi^-$}

time-dependent CP analysis: overview

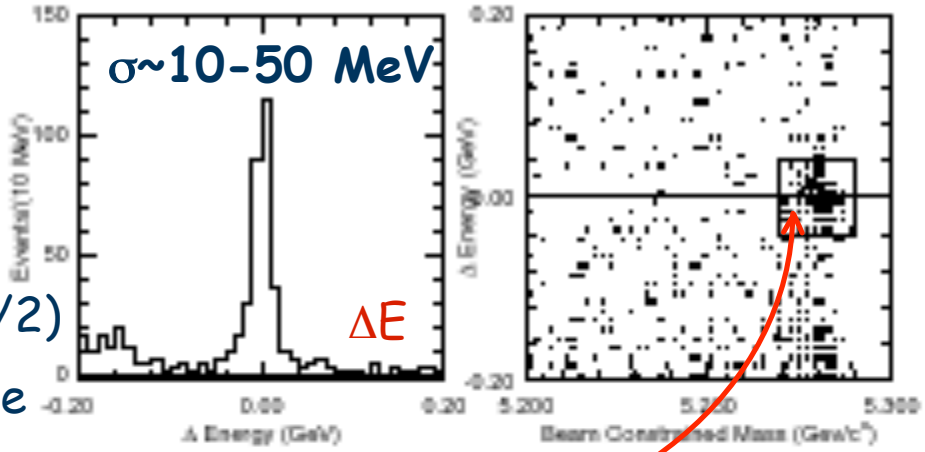
1) CP final state reconstruction exploit
- exclusive pair production of B
- narrow resolution of collision energy

$\Delta E = E^*_{cand} - E^*_{beam} = 0$ ($E^*_{beam} = s^{1/2}/2$)

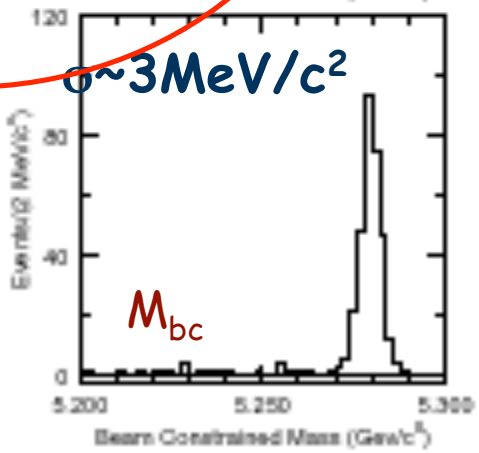
σ~10-50 MeV, depending on mode

M_{bc} (Beam-constrained mass)

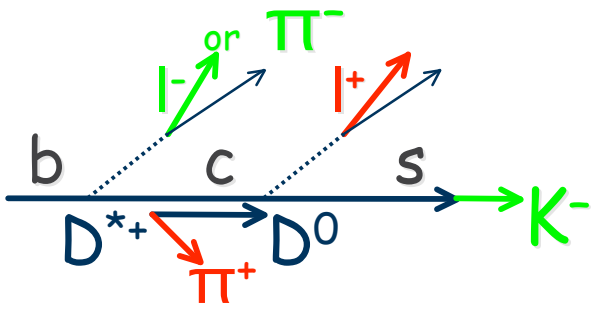
$M_{bc} = (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$



Signal region



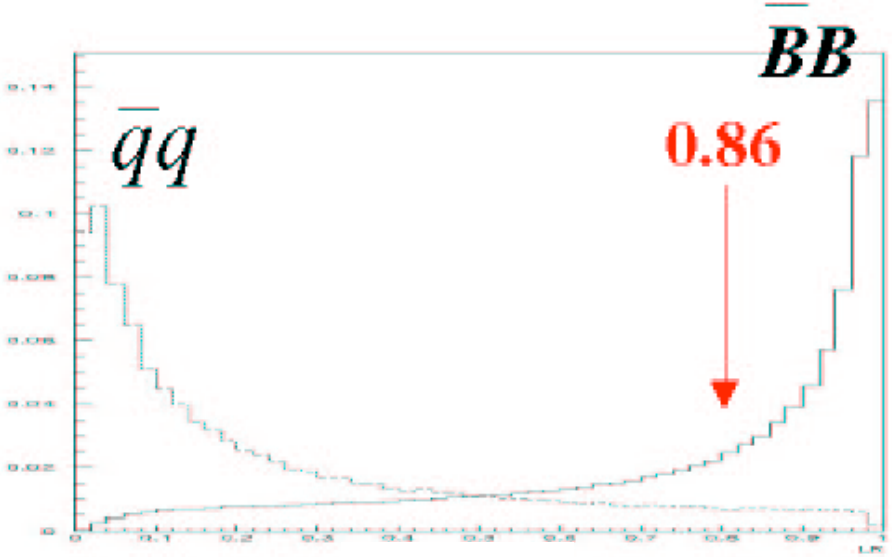
2) Flavor tagging: sign of other b
all remaining particles in the event



high-p lepton (p^*>1.1 GeV): b->l^-
net K charge b->K^-
medium-p lepton, b->c-> l^+
soft π b->c{D^{*+}->$D^0\pi^+$}
hard π b->{c}π^-X
- multidimensional likelihood, ε>99%
- incorrect tag reduces ε, net (28.7±0.5)%

time-dependent CP analysis: overview

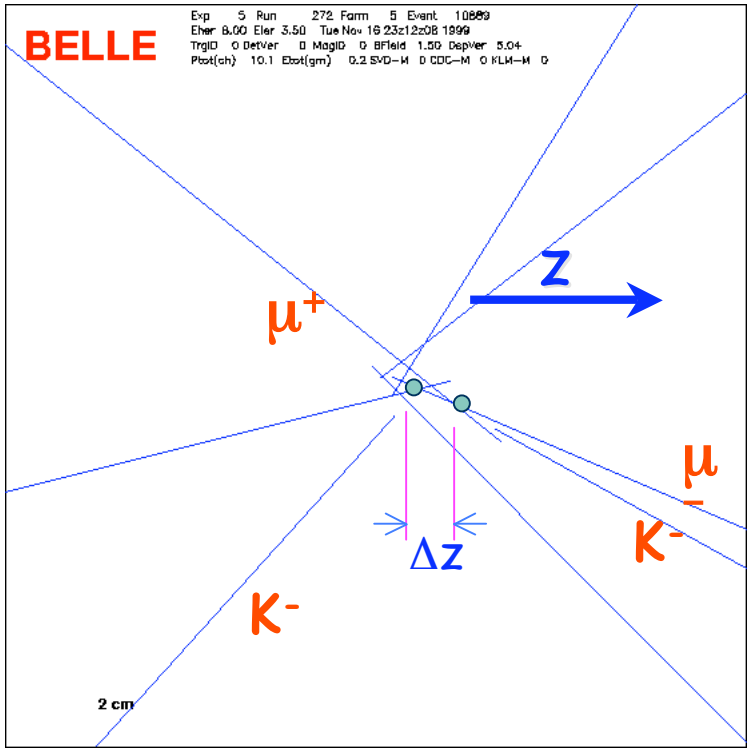
3) Continuum suppression
event parameters, likelihood ratio



$$\frac{L_{sig}}{L_{sig}+L_{bg}}$$

4) Vertex reconstruction

$\Delta t \sim \Delta z/\beta\gamma c$



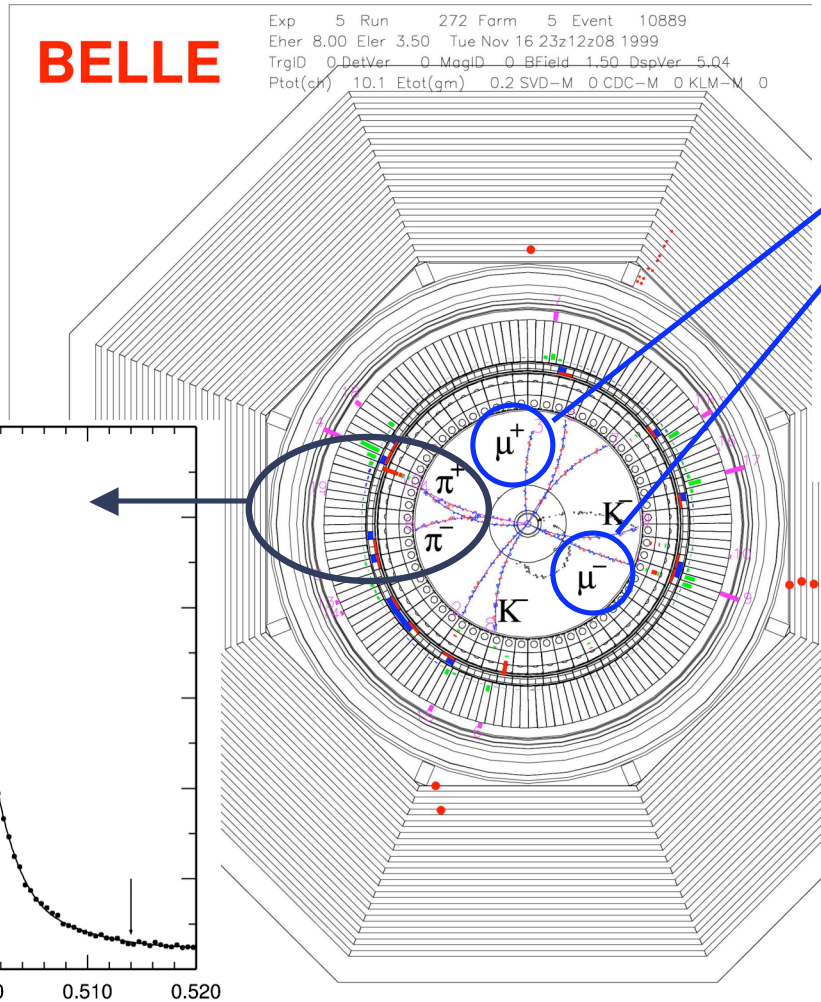
5) Fit to Δt distribution:
unbinned maximum likelihood

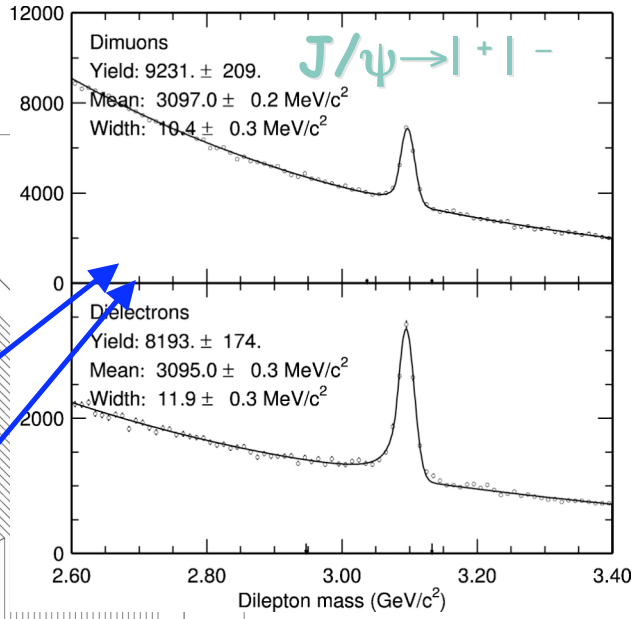
CP eigenstate

"CP-side tag"

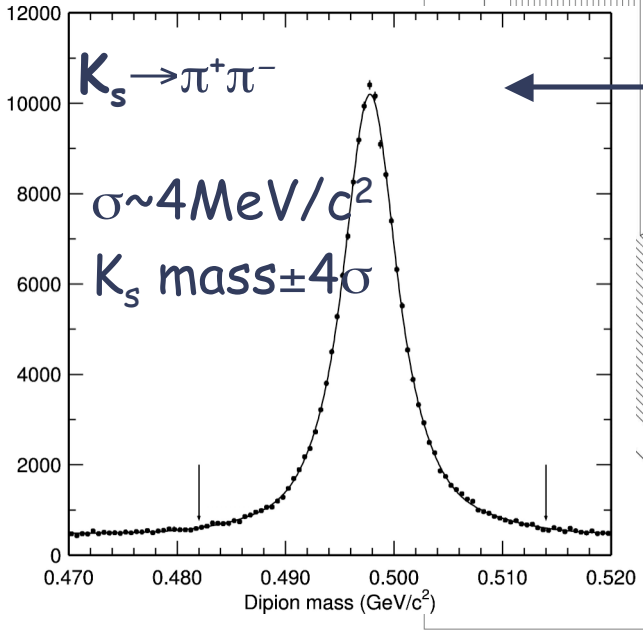
$B^0 \to J/\psi\ K_s(\to\pi^+\pi^-)$

"golden mode"





1lepton+1"not-hadron"

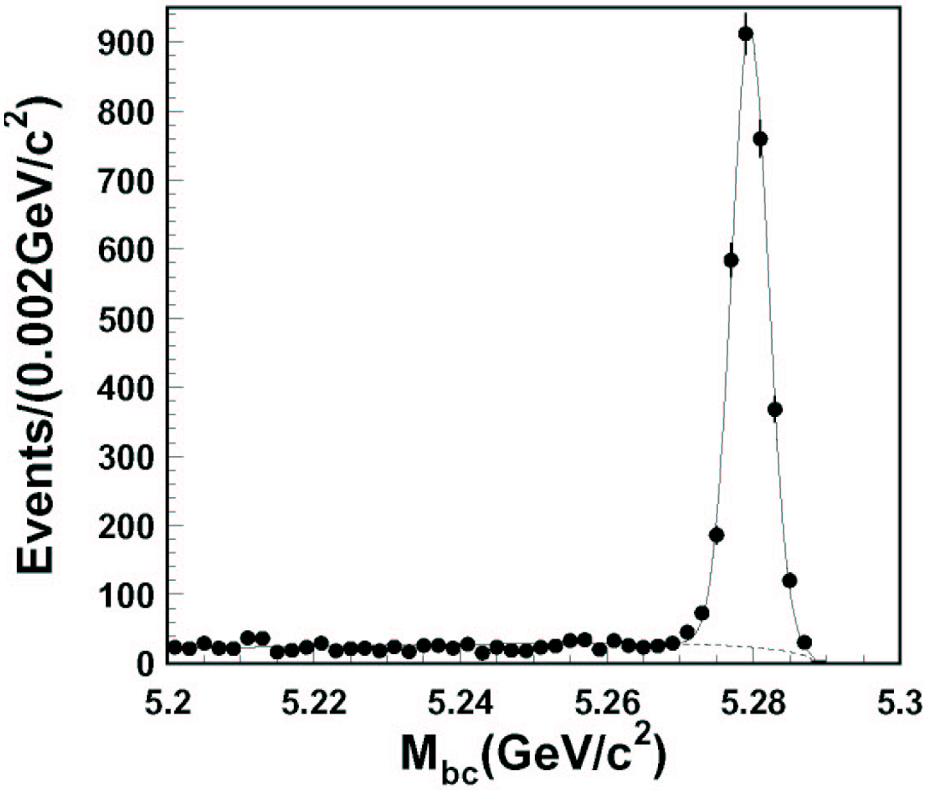


CP eigenstate reconstruction

BELLE-CONF-0436

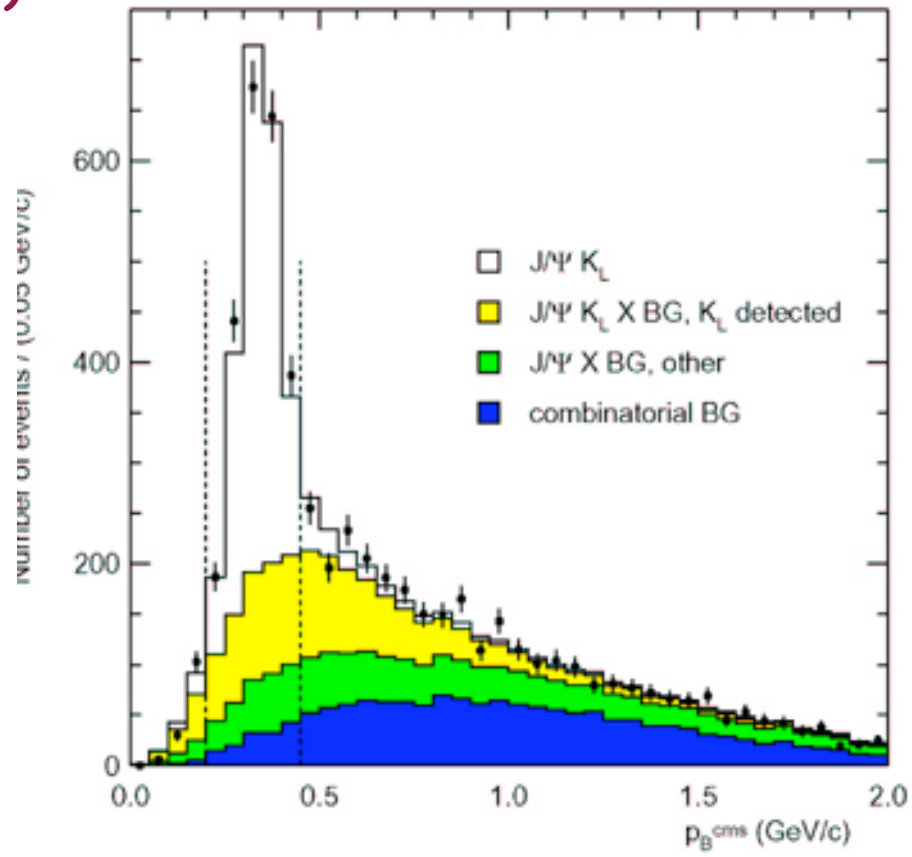
full reconstruction

{charmonium}+K_s tag (*CP*=−1)



"partial" reconstruction

{charmonium}+K_L tag (*CP*=+1)



Asymmetry -> sin2ϕ_1

140 fb^{-1}

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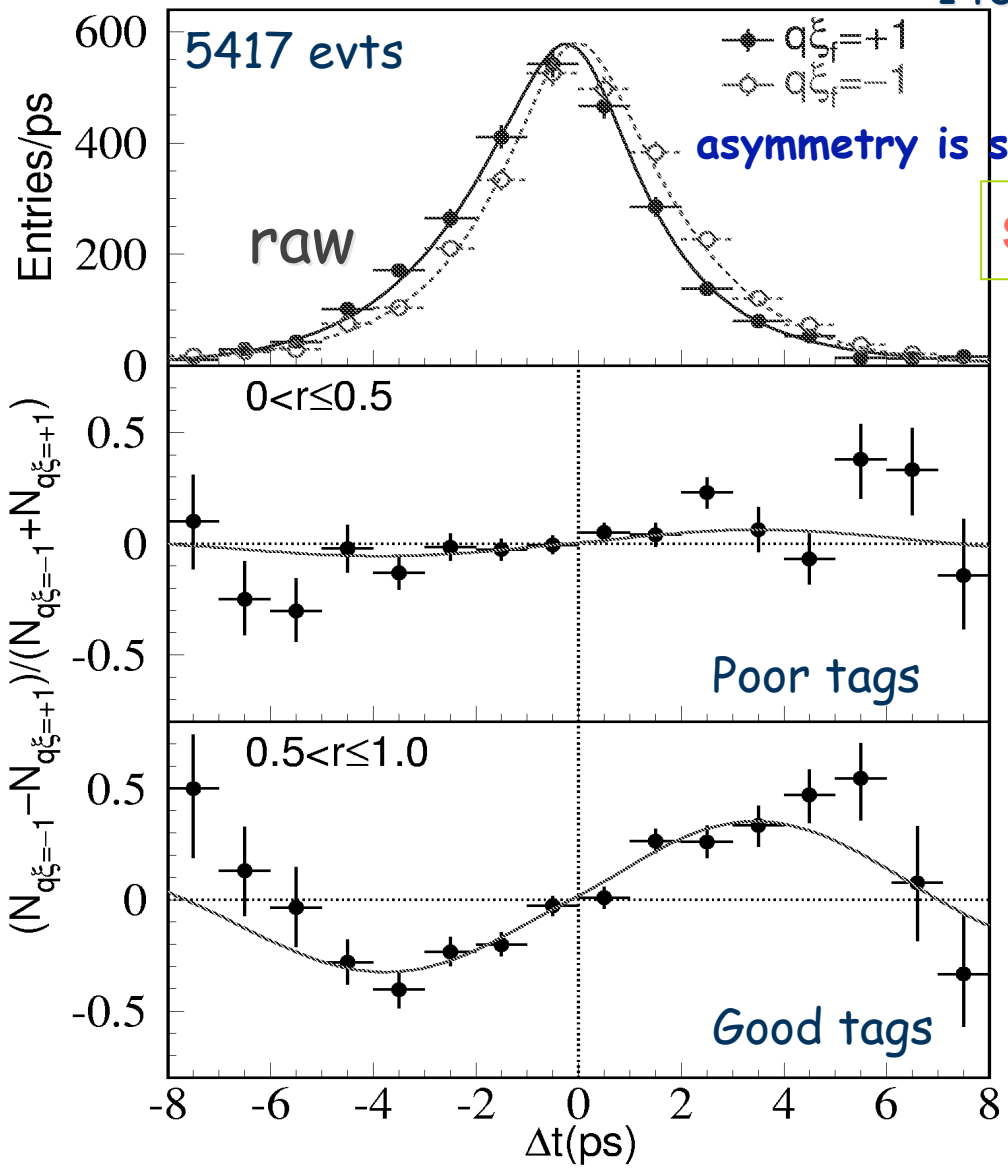
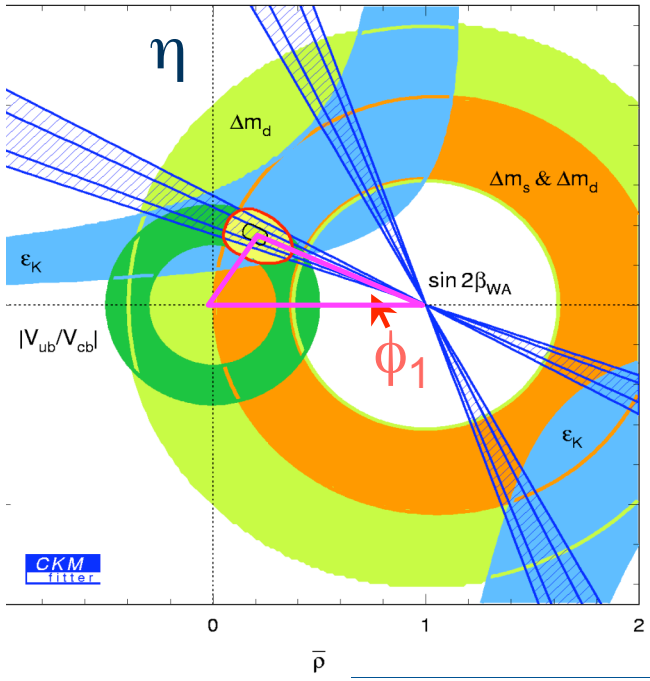


asymmetry is seen in raw data

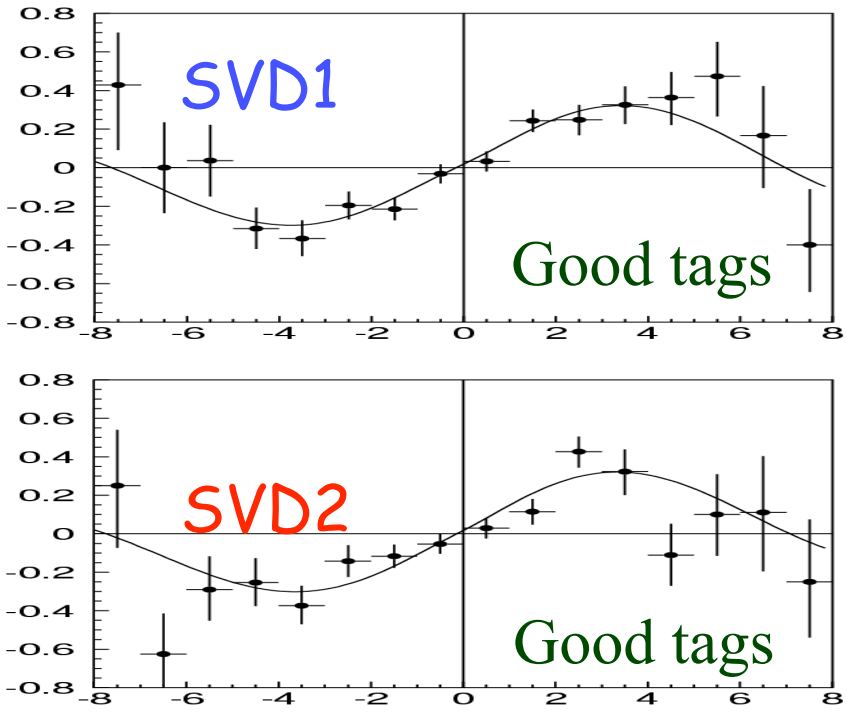
$\sin 2\phi_1 = 0.728 \pm 0.056 \pm 0.023$

consistent with no direct CP violation



Check on vertexing: $\sin 2\phi_1$ ($B^0 \to J/\psi\, K_{S/L}$)

[hep-ex/0409049]



SVD1: 152M $B\bar{B}$

$$\mathcal{S} = 0.696 \pm 0.061 \text{ (stat)}$$
$$\mathcal{A} = 0.011 \pm 0.043 \text{ (stat)}$$

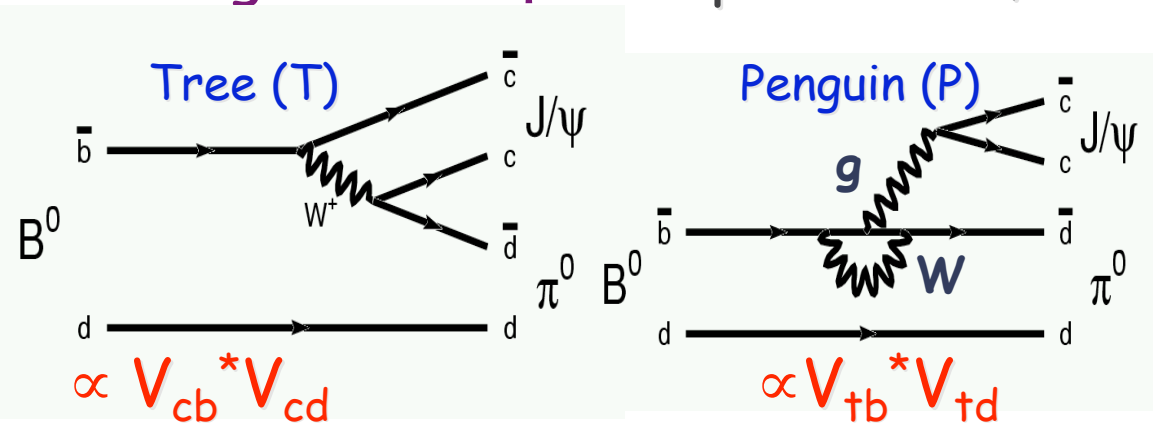
SVD2: 123M $B\bar{B}$

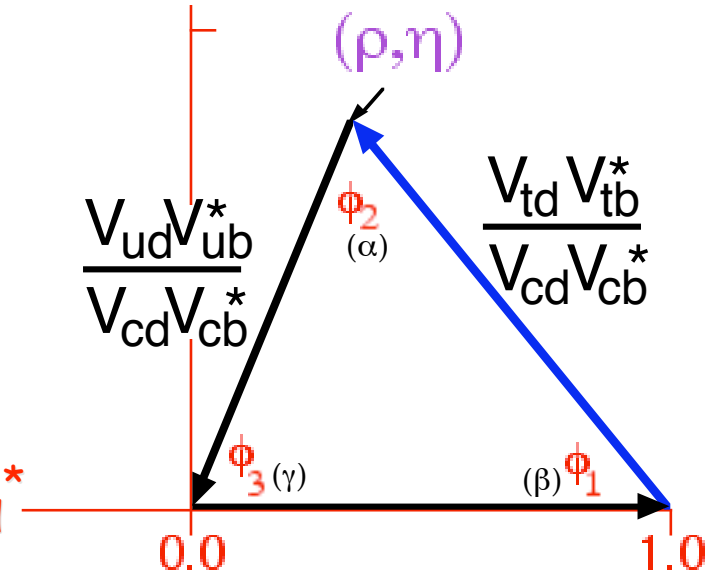
$$\mathcal{S} = 0.629 \pm 0.069 \text{ (stat)}$$
$$\mathcal{A} = 0.035 \pm 0.044 \text{ (stat)}$$

$\sin 2\phi_1$ (World Av.)=0.726±0.037

Other paths to CP asymmetry

e.g. B -> J/ψπ⁰ 2 processes, different phases, + mixing





mixing+ "
$\propto V_{tb}^{*2} V_{td}^{2} V_{cb} V_{cd}^{*}$

mixing+ "
$\propto V_{tb}^{*2} V_{td}^{2} V_{tb} V_{td}^{*}$

Bottom line: "direct" CP asymmetry possible

$$q = \begin{pmatrix} +1 \text{if } B_{t=0} = B^0 \\ -1 \text{if } B_{t=0} = \bar{B}^0 \end{pmatrix}$$

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + q \cdot [\mathcal{A}\cos(\Delta m \Delta t) + \mathcal{S}\sin(\Delta m \Delta t)])$$

"direct" asym

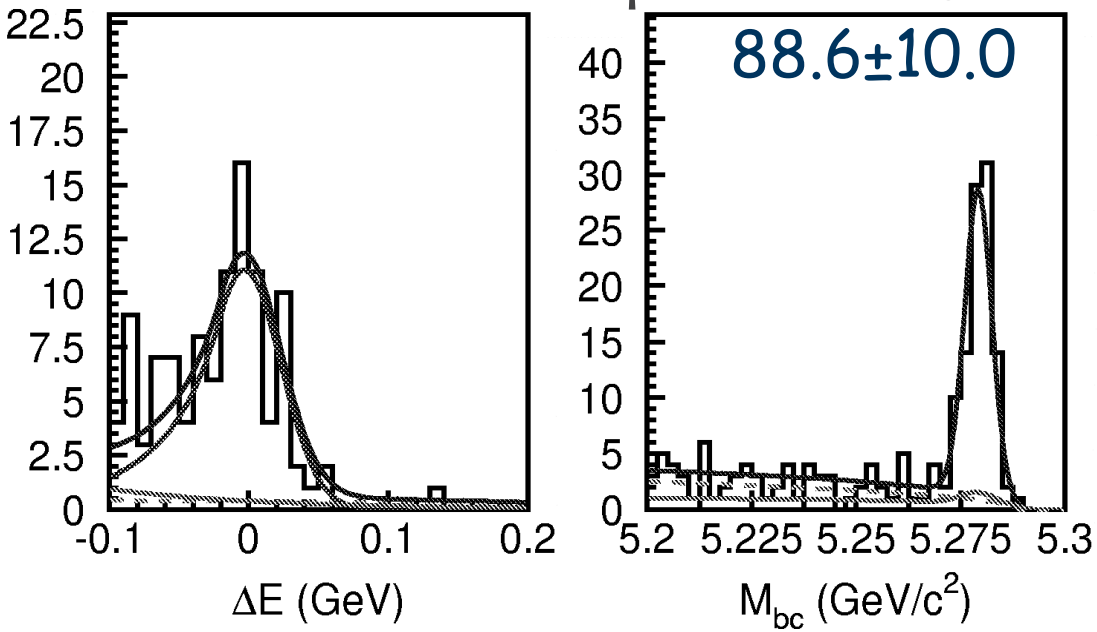
relation to ϕ_1 depends on T/P relative amplitudes, strong phase (not known)

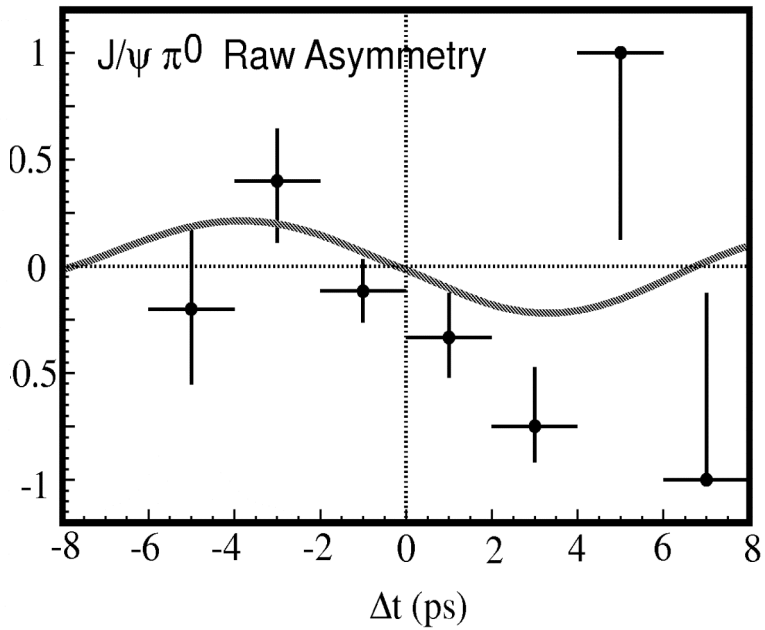
expect S = -sin2ϕ_1 if penguin is small

b->{c $\bar{c}$ d}: B->J/ψ π^0 (CP=+1)

PRL93,260801 (2004)

B->J/ψ π^0 140 fb^{-1}





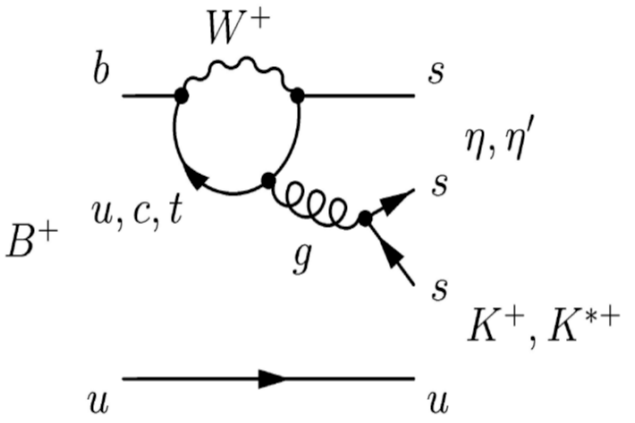
$S = -0.72 \pm 0.42 \pm 0.09$

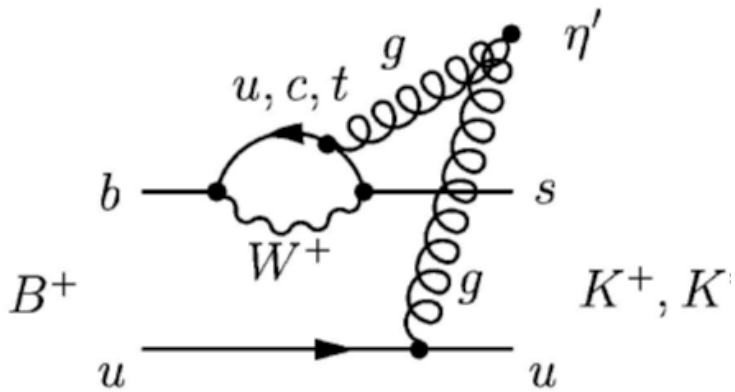
$A = -0.01 \pm 0.29 \pm 0.03$

$\sin 2\phi_1$ (World Av.)=0.726±0.037

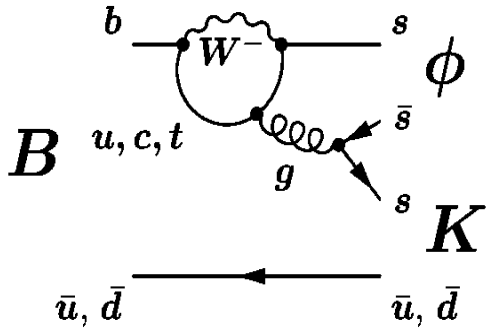
More time-dependent sin2ϕ_1 – or new physics?

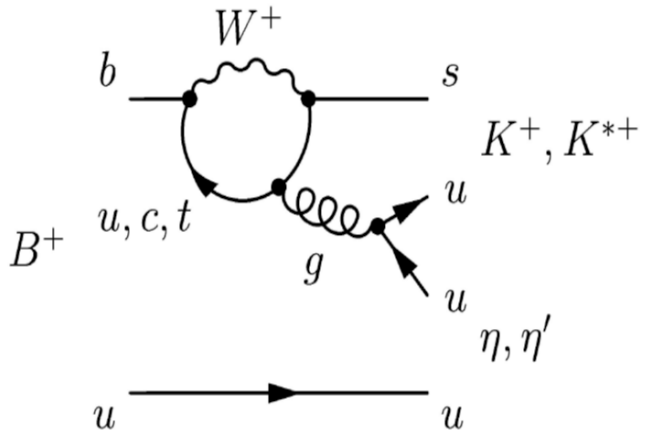
modes dominated by b->sq$\bar{q}$ penguins

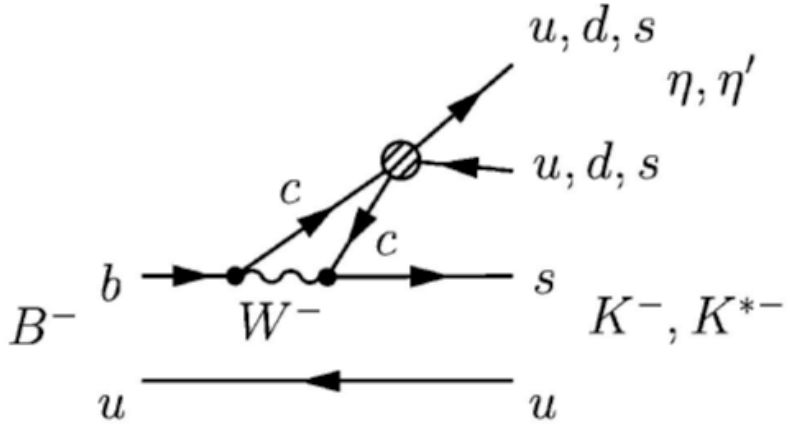




Theoretically cleanest

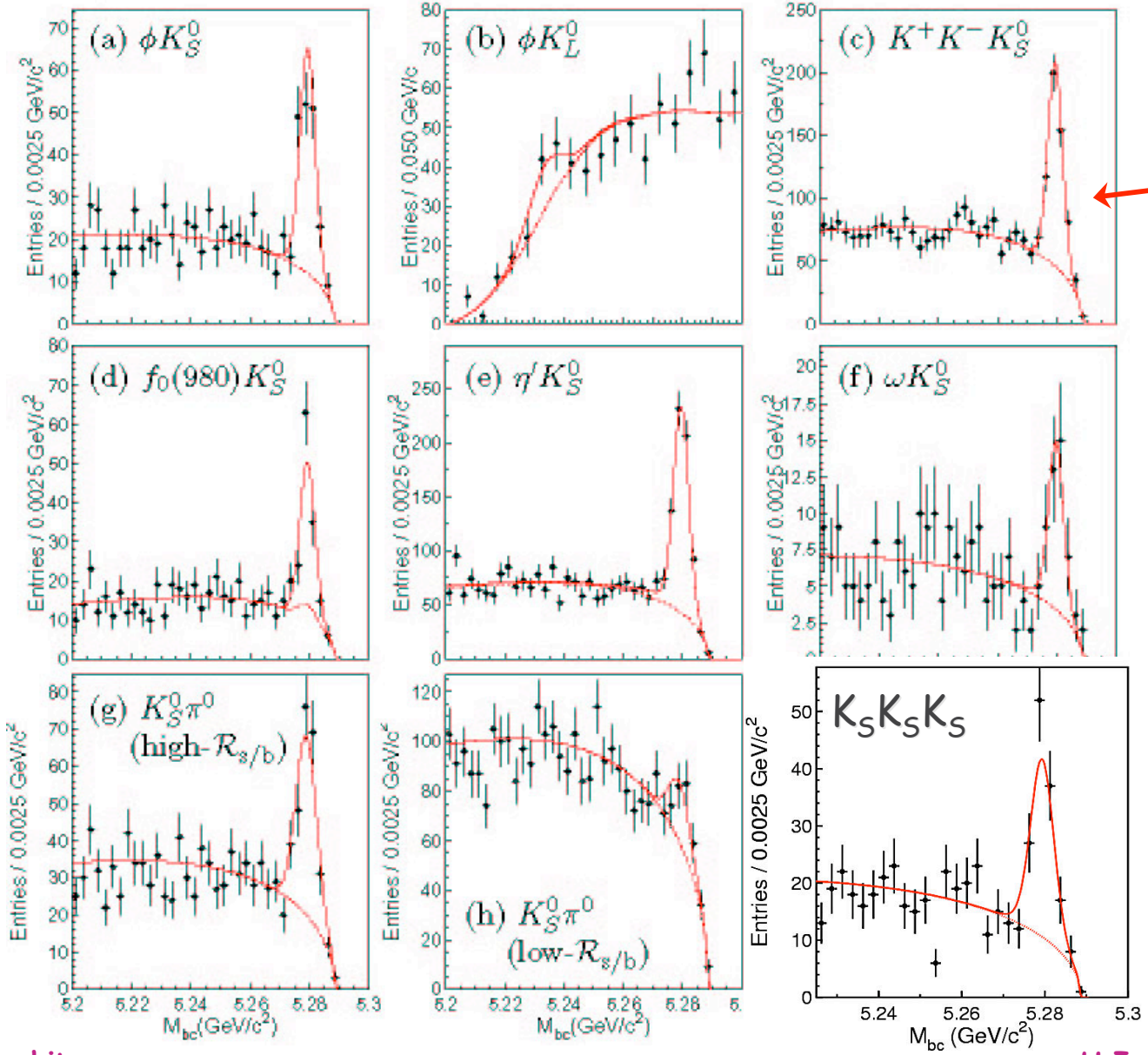






in the absence of New Physics, S = sin2ϕ_1

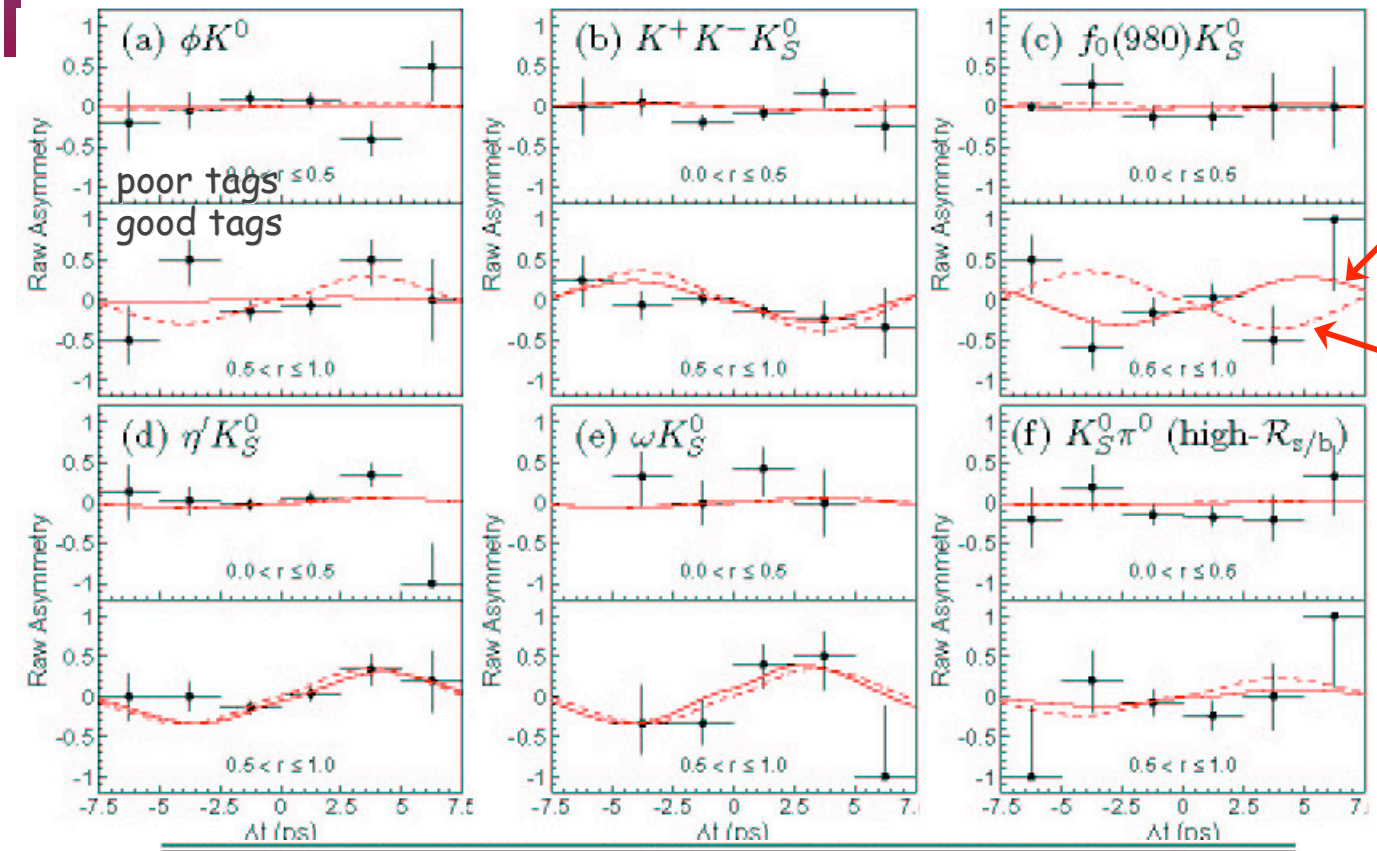
Reconstruction of b->sqq



253 fb^{-1}

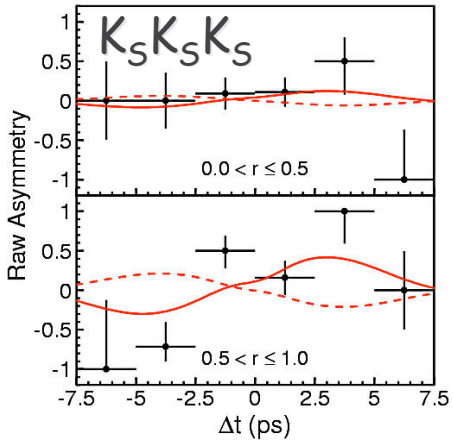
CP = +1 (angular analysis)

Time-dependence:



Projected fit

SM expectation



Mode	SM expectation for $\mathcal{S}$	$\mathcal{S}$	$\mathcal{A}$
ϕK^0	$+\sin 2\phi_1$	$+0.06 \pm 0.33 \pm 0.09$	$+0.08 \pm 0.22 \pm 0.09$
$K^+K^-K^0_S$	$-\sin 2\phi_1$	$-0.49 \pm 0.18 \pm 0.04$	$-0.08 \pm 0.12 \pm 0.07$
$f_0(980)K^0_S$	$-\sin 2\phi_1$	$+0.47 \pm 0.41 \pm 0.08$	$-0.39 \pm 0.27 \pm 0.08$
$\eta' K^0_S$	$+\sin 2\phi_1$	$+0.65 \pm 0.18 \pm 0.04$	$-0.19 \pm 0.11 \pm 0.05$
ωK^0_S	$+\sin 2\phi_1$	$+0.75 \pm 0.64^{+0.13}_{-0.16}$	$+0.26 \pm 0.48 \pm 0.15$
$K^0_S\pi^0$	$+\sin 2\phi_1$	$+0.30 \pm 0.59 \pm 0.11$	$-0.12 \pm 0.20 \pm 0.07$
$K_SK_SK_S$	$-\sin 2\phi_1$	$+1.26 \pm 0.68 \pm 0.18$	$+0.54 \pm 0.34 \pm 0.08$

World Average sin2ϕ_1 from *b->s* penguins

$Sin2\phi_1(b\to sq\bar{q})$ =

- 0.39 ± 0.11 (Belle)
- 0.42 ± 0.10 (*BABAR*)

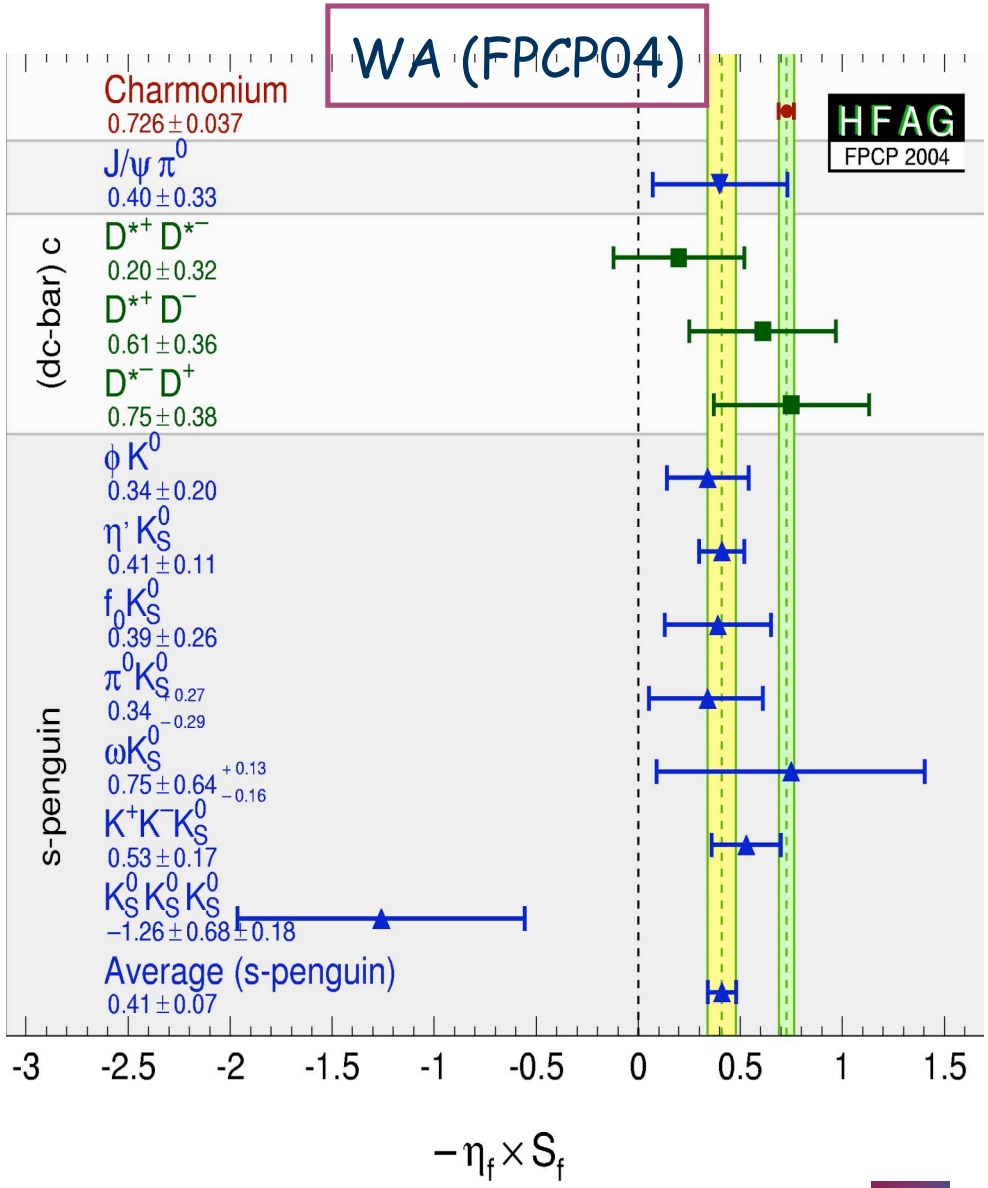
World Average (WA)

$sin2\phi_1(b\to sq\bar{q})$= 0.41 ± 0.07

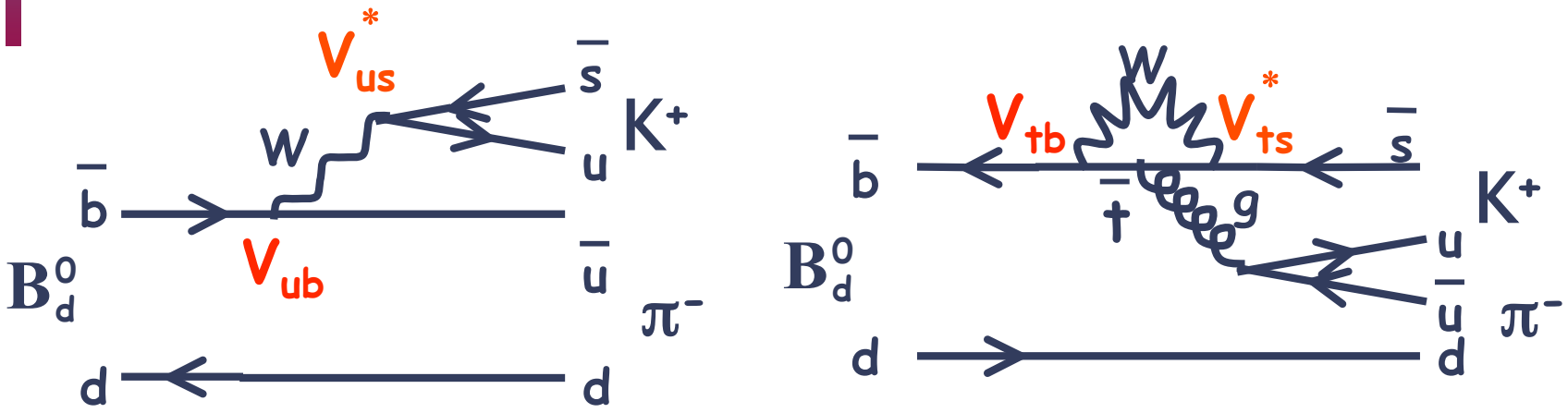
Compare with $c\bar{c}s$:

$sin2\phi_1(b\to c\bar{c}s)$ = 0.726 ± 0.037

CL = 1.2×10^{-4} (3.8σ)



$B^0 \to K\pi$



Tree-penguin interference -> direct CP violation

$$\mathcal{A}_{CP} = \frac{N(\bar{B} \to \bar{f}) - N(B \to f)}{N(\bar{B} \to \bar{f}) + N(B \to f)}$$

expect $A_{CP}(K^+\pi^-) \sim A_{CP}(K^+\pi^0)$

$A_{CP}(B^0 \to K\pi)$

275M $B\bar{B}$

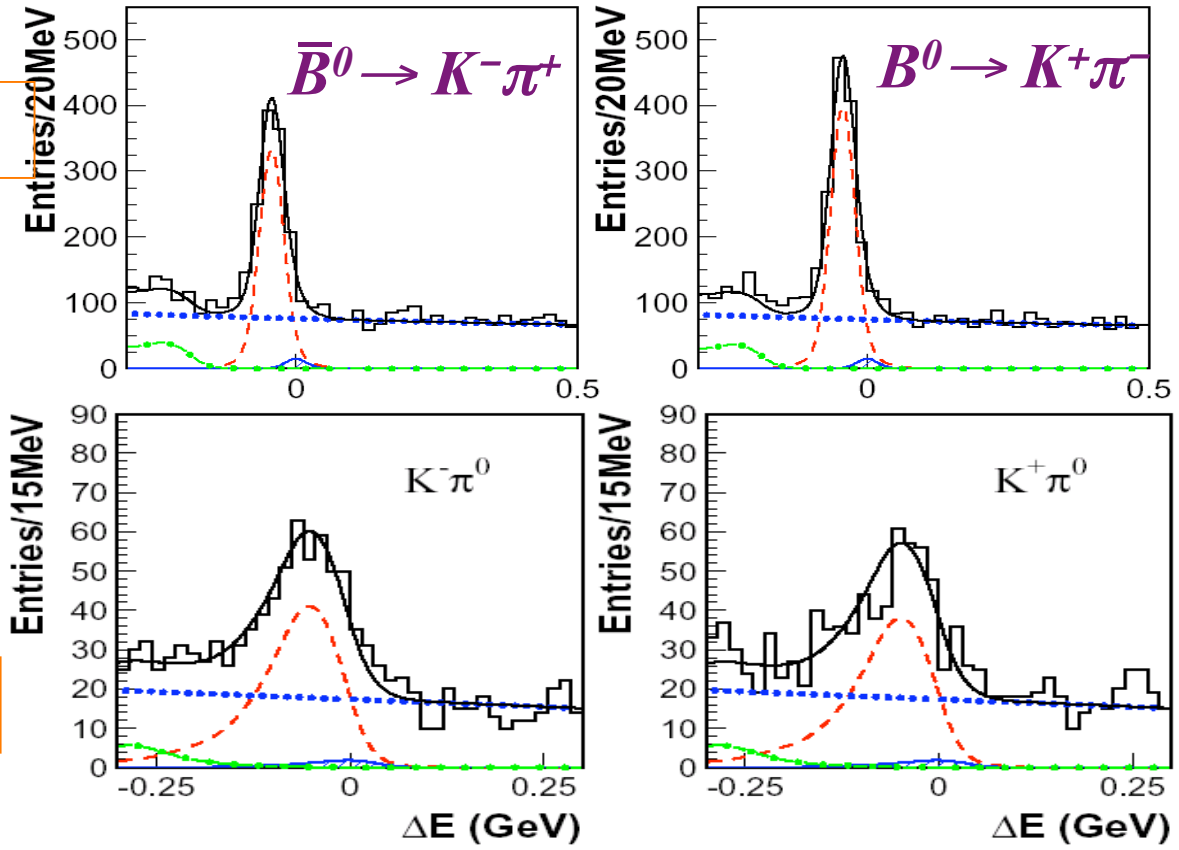
[PRL 93, 191802 (2004)]

signal: 2139 ± 53

A_{CP}= -0.101±0.025±0.005

3.9σ significance

[PID eff. bias correction:
δA = -0.01 ± 0.004]



Signal: 728 ± 34

A_{CP}= +0.04±0.05±0.02

If $A_{CP}(K^+\pi^-) \neq A_{CP}(K^+\pi^0)$ -> anomalously large e.g. EW penguin or new physics

Summary

Belle in 2005:

- KEKB *luminosity* $1.40 \times 10^{34} cm^{-2} s^{-1}$ (design: 1×10^{34}); >350M B pairs
- $\sin 2\phi_1$ via $\psi K^{(*)0}$ is now a "precision" measurement
- alternative probes of $\sin 2\phi_1$ (or new physics) – suggestive
  - $B \to J/\psi \pi^0$ - penguin may be small (need more data)
  - penguin-dominated B -> sqq - hints of new physics?
- direct CP violation in $K\pi$, difference $K^+\pi^-$ vs $K^+\pi^0$?
- observations/hints in many modes, possibly CP in future

Next

- aiming for 500 fb^{-1} by summer
- Luminosity > design
- the CP challenge: heating up - stay tuned!