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

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Introduction: Particles & Interactions

Fundamental particles (relativistic QM)

- massless, relativistic QM states
- "discretely symmetric"

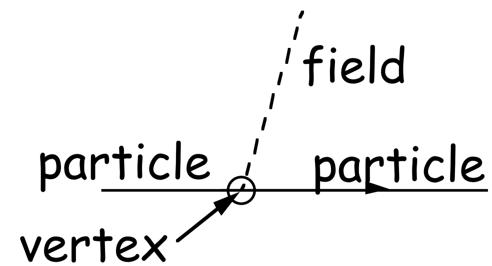
Parity	Time reversal	Charge conjugation
space	time	energy
r <-> -r	t <-> -t	f <-> anti-f

Universe

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

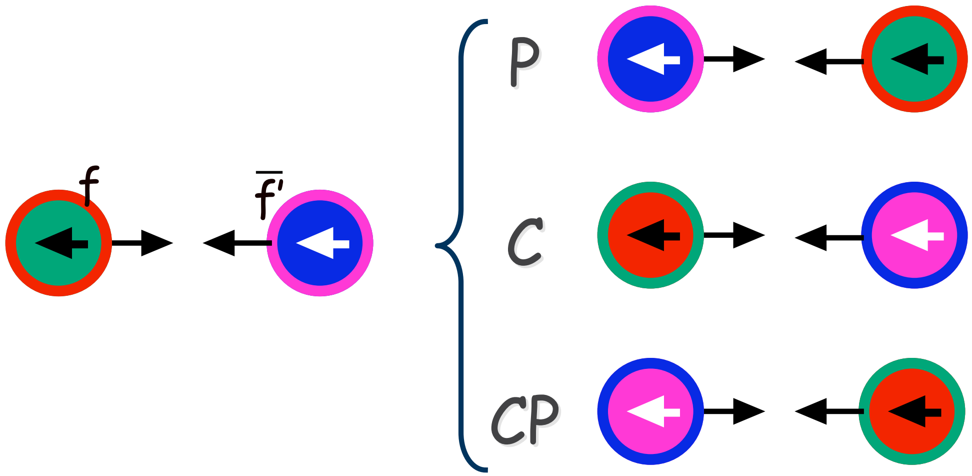
How can these be reconciled??

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

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

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

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

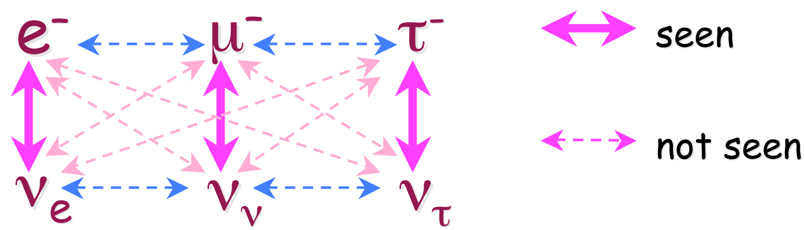
Equal only if relative phase of g,g'=0

How does weak force violate CP?

Standard Model = 12 fermion flavors (+antifermion)

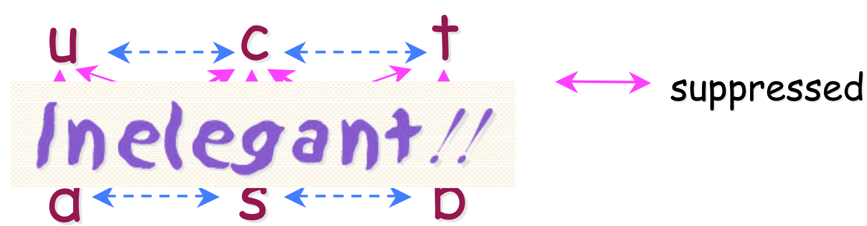
- 3 generations(distinguished only by mass)x2 typesx2 ea(strong & EM couplings) (stable, but for weak interaction)
- leptons: ~universal coupling, no generation x-ing

W± "charged current"



Z^0 "neutral current"

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



Elegance restored: GIM mechanism

Picture

$$\{\text{matrix of couplings}\} = g_F \times \begin{matrix} & d & s & b \\ u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{matrix} \quad \text{can be expressed} \quad g_F \times \begin{matrix} & d' & s' & b' \\ u & 1 & 0 & 0 \\ c & 0 & 1 & 0 \\ t & 0 & 0 & 1 \end{matrix}$$

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

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

$\mathcal{M}$: 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

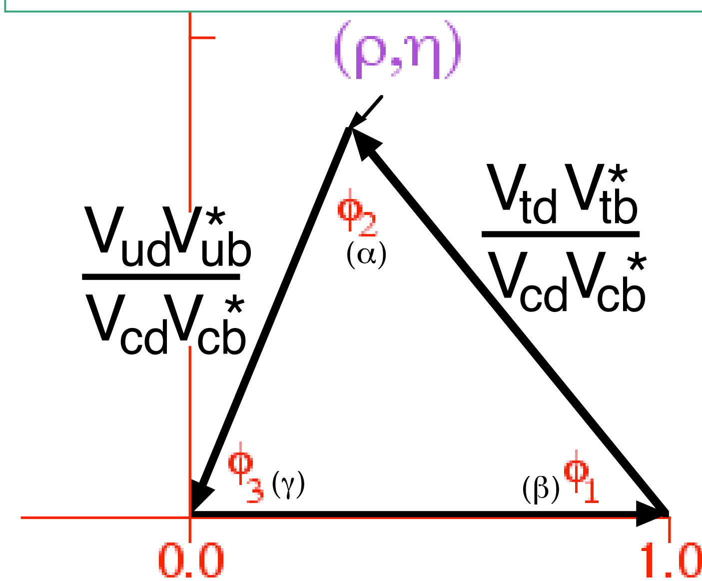
$$V_{ji}^* V_{jk} = \delta_{ik}$$

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

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

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

(ρ, η): "unitarity triangle"



Self-consistent if CKM is correct

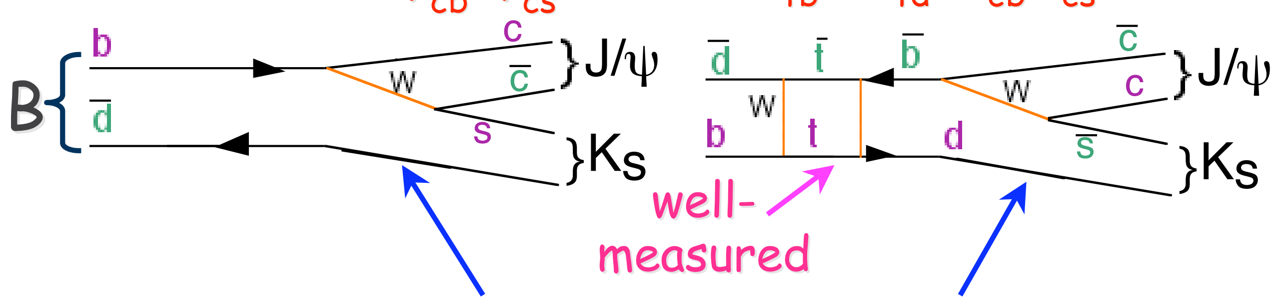
CP asymmetries with CKM

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

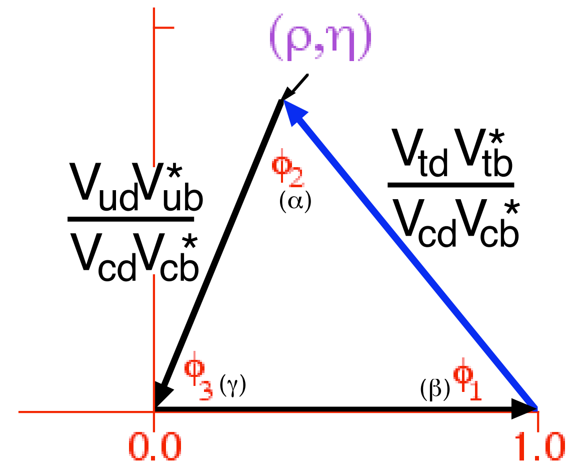
First goal: sin $2\phi_1$ in "golden mode" B -> J/ψ K_s(Sanda/Bigi/Carter)

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

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



identical hadronic processes



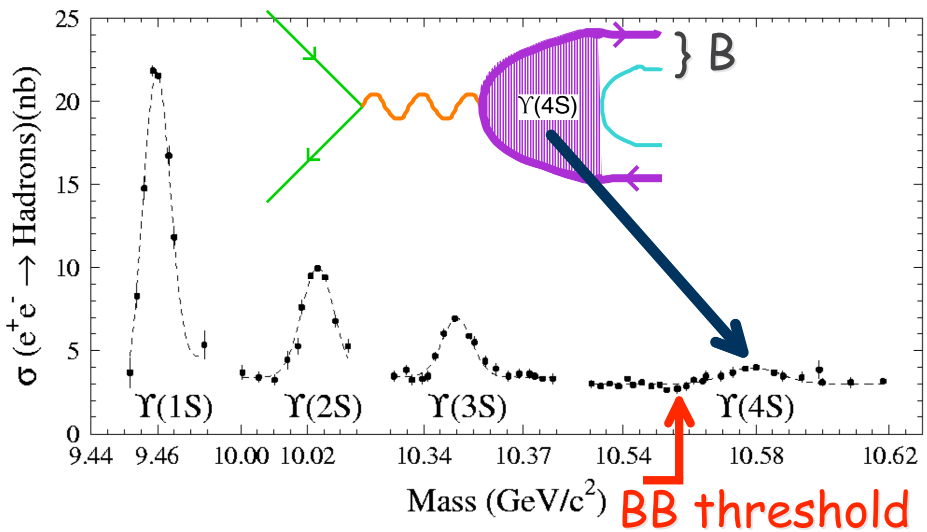
CP asymmetry from x-term(s) - no theoretical uncertainty: $\propto \arg(V_{td}^2) = 2\phi_1$

Bottom line: CP-dependent oscillation in time:

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

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

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



BB threshold

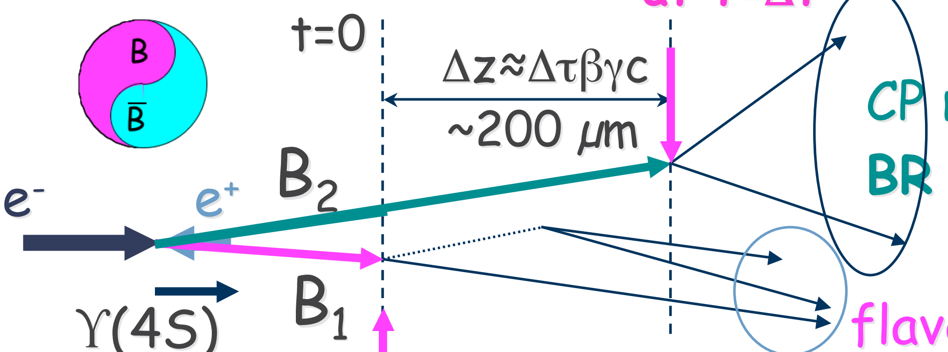
Δt by asymmetric energy e^+e^- -> Υ(4S)

(symmetric Υ(4S): CLEO 1979-2001)

Need

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

2nd decay at t=Δt



CP mode @ t=Δt

BR < 10^{-3}

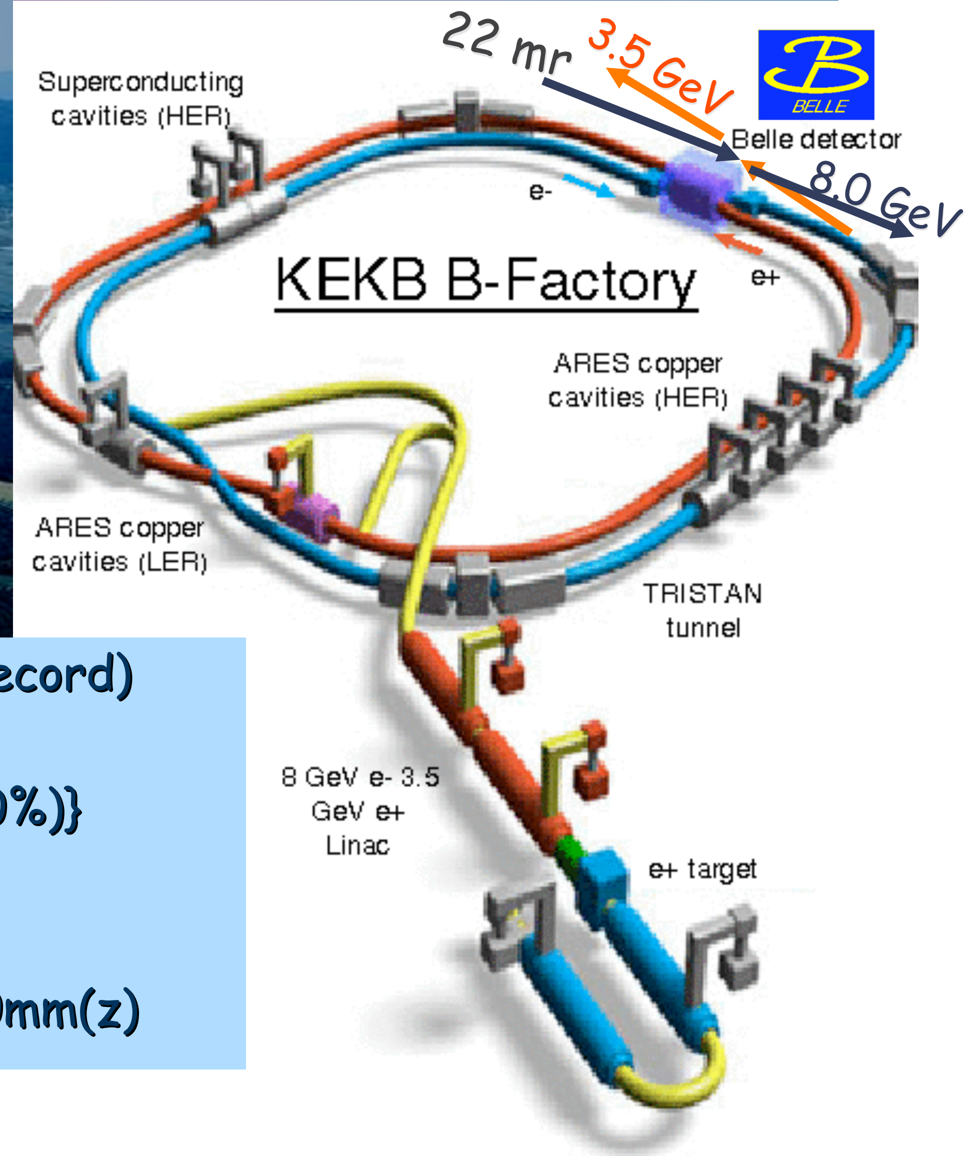
CP=-1, conserved

first B decay (t=0), break CP

flavor tag @t=0: e, μ, K±, ...

effective eff ~30%

Colliding beams: KEKB



L_{max} = 1.52 X 10^{34} $cm^{-2}s^{-1}$ (world record)

Data (6/1999-3/2005)

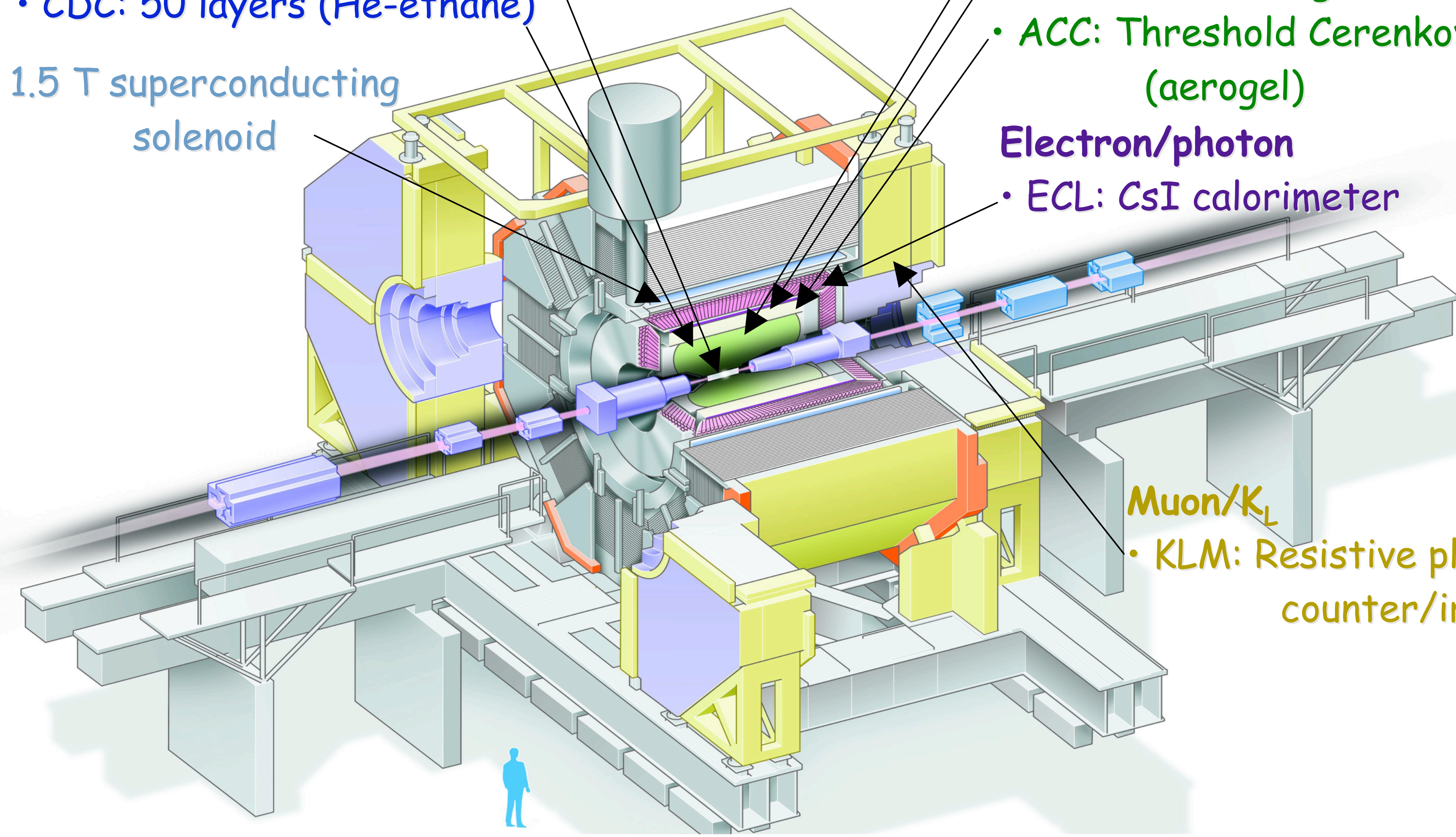
$\int Ldt$ = 380 fb^{-1}@{Υ(4S)+off(~10%)}

(>3.8x10^8 B events)

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

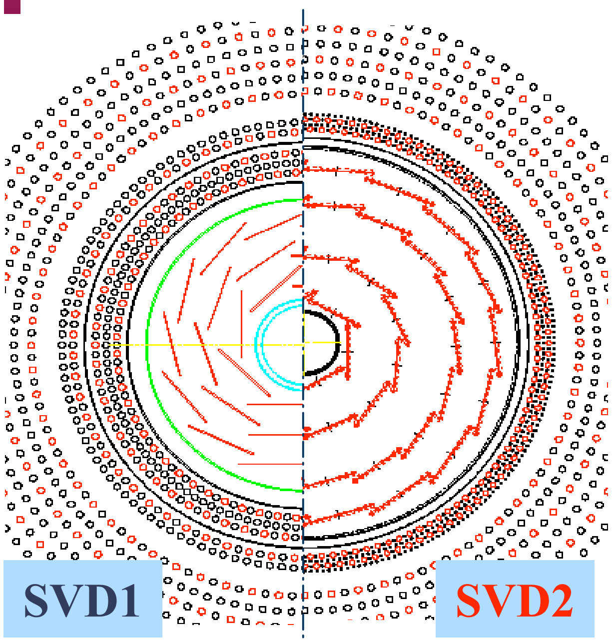
IP size = 77μm(x) x 2.0μm(y) x 4.0mm(z)

The Detector



SVD Upgrade

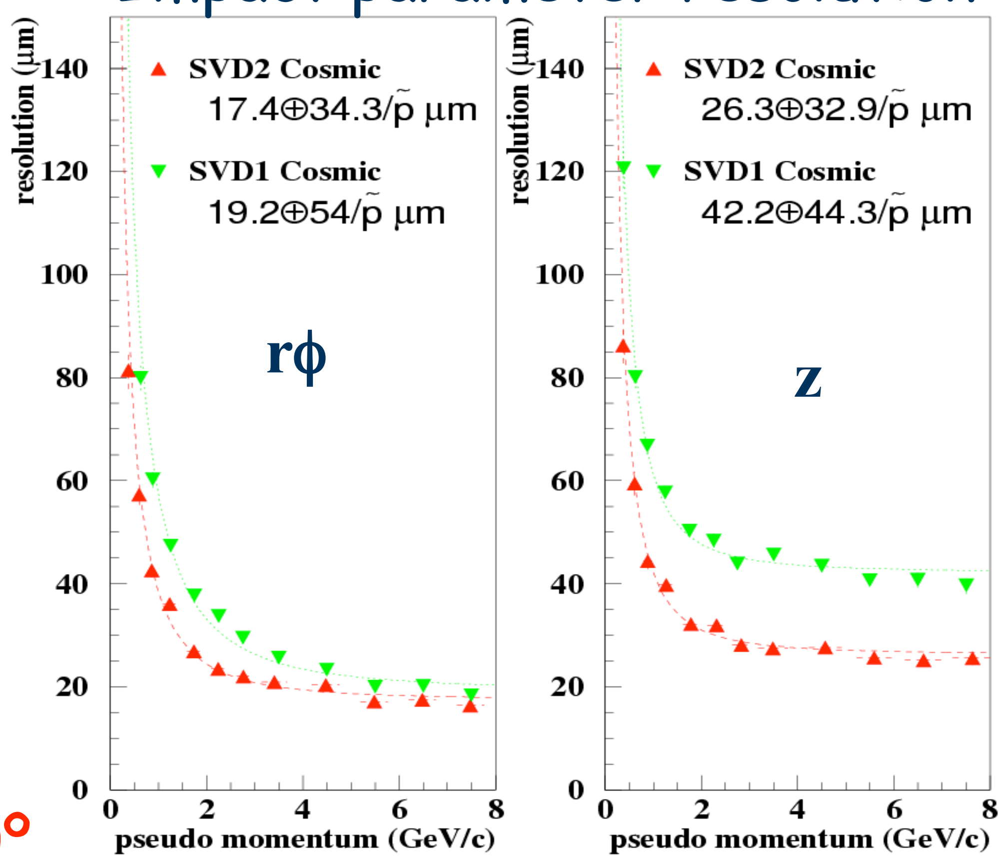
2003 summer



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

-> Better I.P. resolution

Impact parameter 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.
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 collaborators

(authors vary, each paper)

Belle physics

120±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

- time-dependent CP asymmetry
  - ϕ_1: update $J/\psi K_S$,$J/\psi K_L$
  - ~ ϕ_1: ϕK_s,$J/\psi\pi^0$,$K^-\pi^+$,$\eta' K_s$,f^0K_s,π^0K_s, ωK_S,$K^+K^-K_s$,$K_sK_sK_s$,ηK^+, $\eta\pi^+$
  - ~ ϕ_2: $\pi^+\pi^-$,$\rho^+\pi^0$,$\rho^+\pi^-$ ~ ϕ_3: $D^{*+}\pi^-(2\phi_1+\phi_3)$
- evidence/observation
  - $B\to K^*l^+l^-$, $\pi^0\pi^0$, D^+D^-, $\pi^0\rho^0$, $K^*\rho$, ...
- method for ϕ_3: Dalitz plot analysis
  - D^0K^+ $\{D^0\to K_s\pi^+\pi^-\}$

time-dependent CP analysis: overview

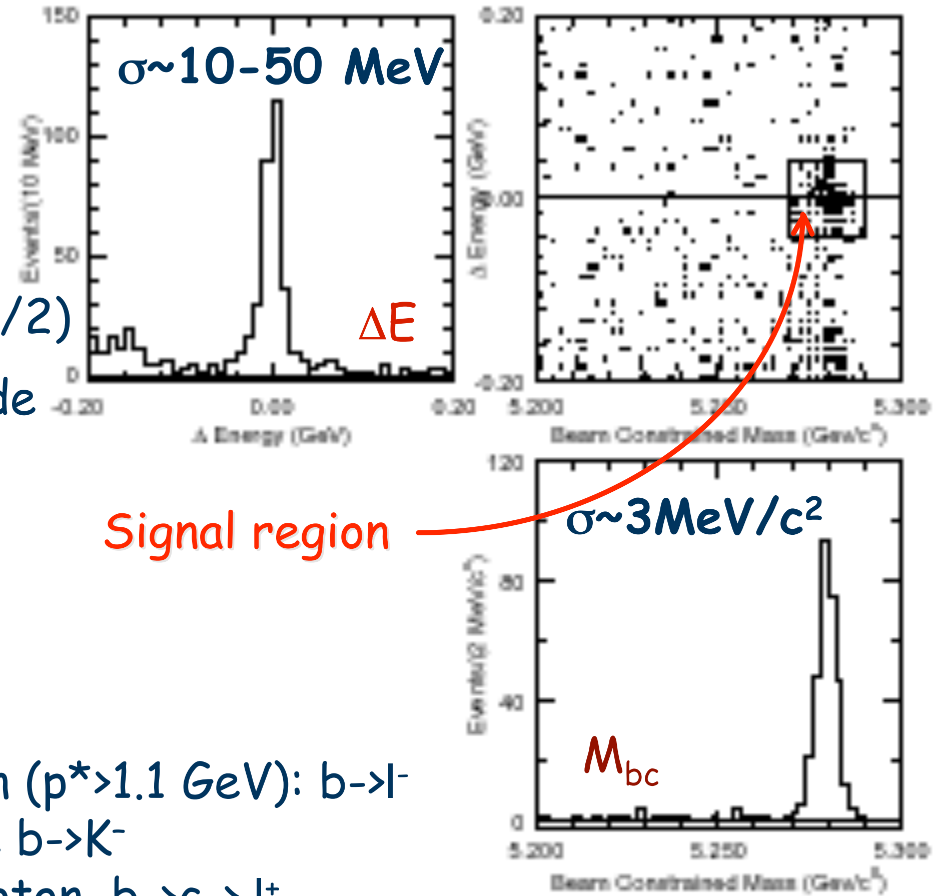
1) CP final state reconstruction
exploit
- exclusive pair production of B
- narrow resolution of collision energy

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

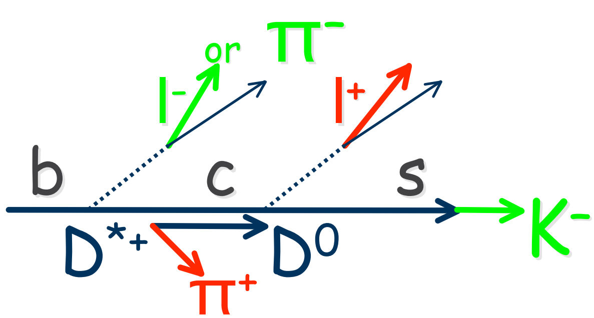
σ~10-50 MeV, depending on mode

M_{bc} (Beam-constrained mass)

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



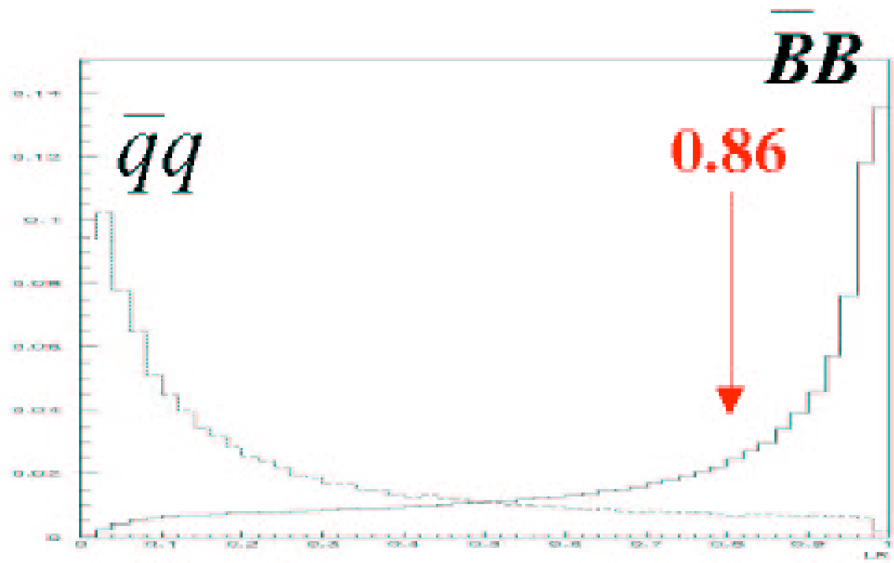
2) Flavor tagging: sign of other b
all remaining particles in the event



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

3) Continuum suppression

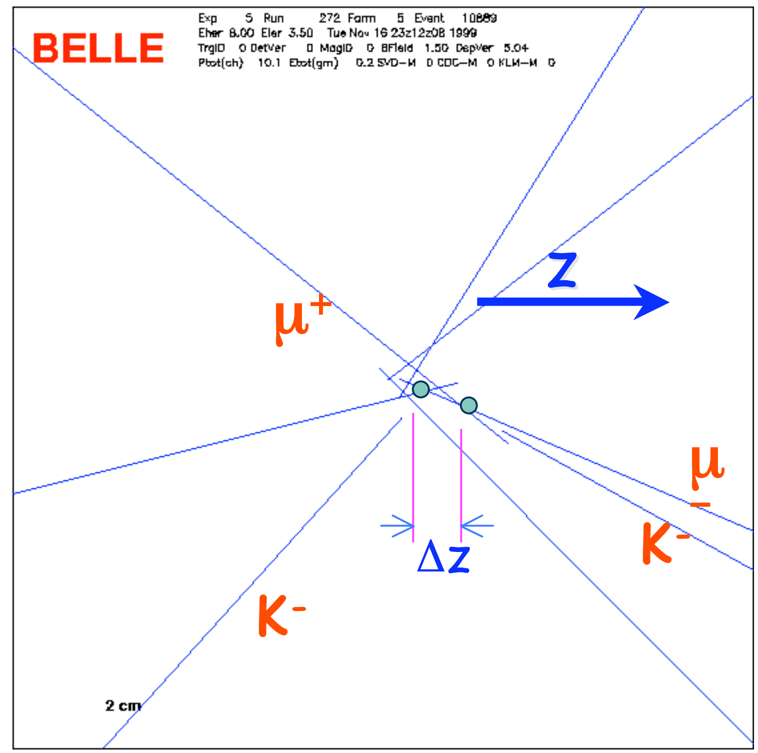
event parameters, likelihood ratio



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

4) Vertex reconstruction

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



5) Fit to Δt distribution:

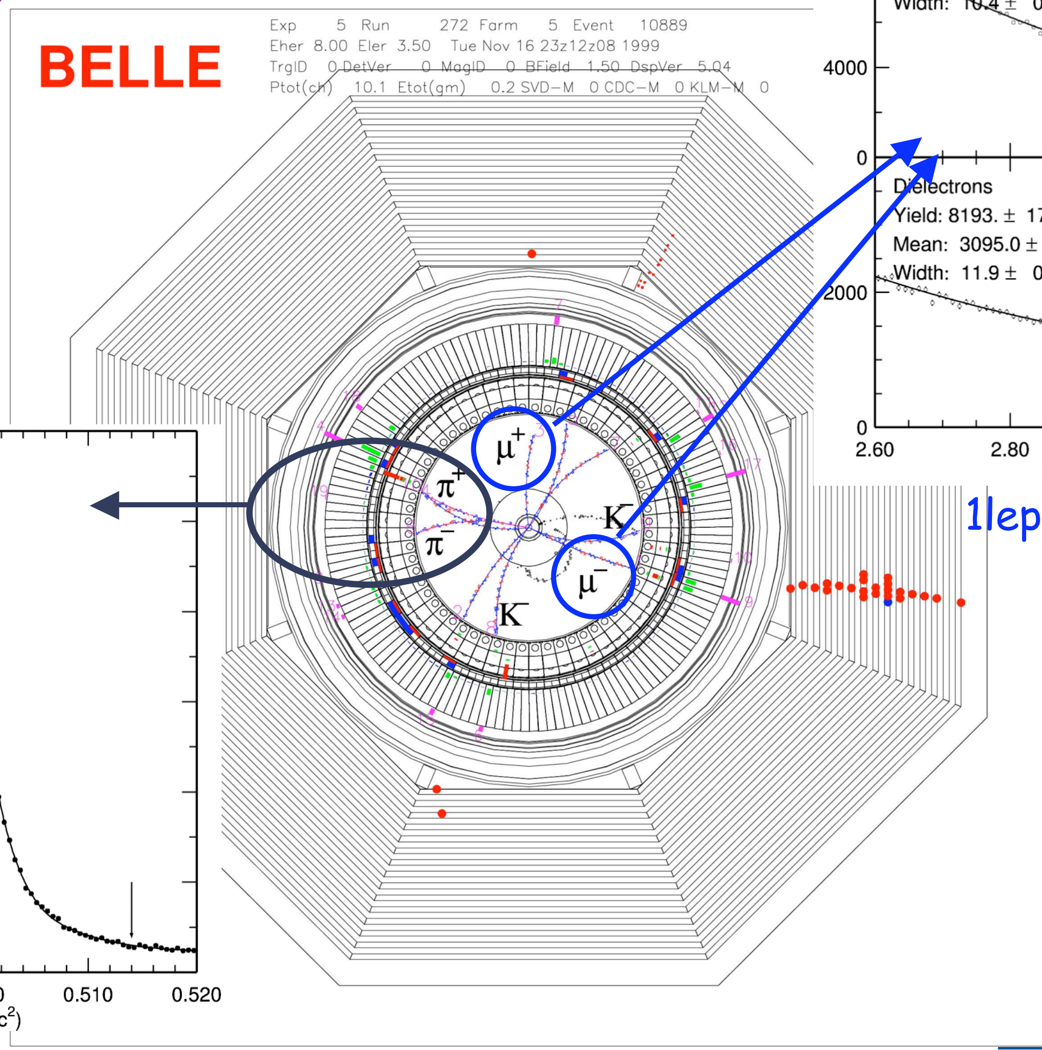
unbinned maximum likelihood

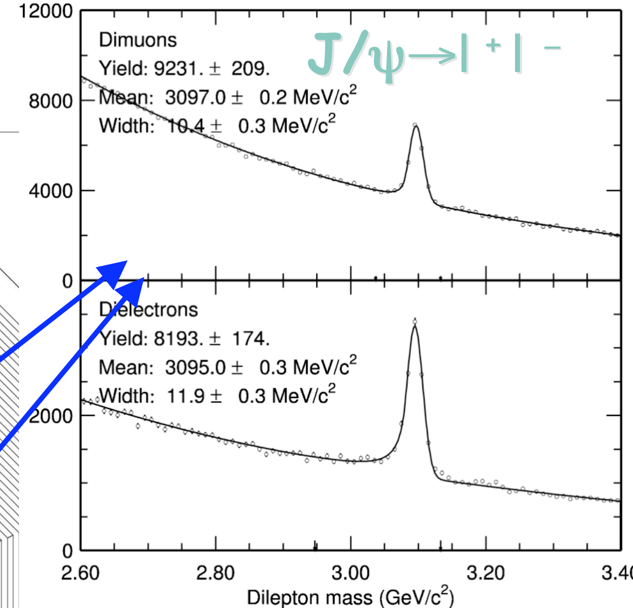
CP eigenstate

"CP-side tag"

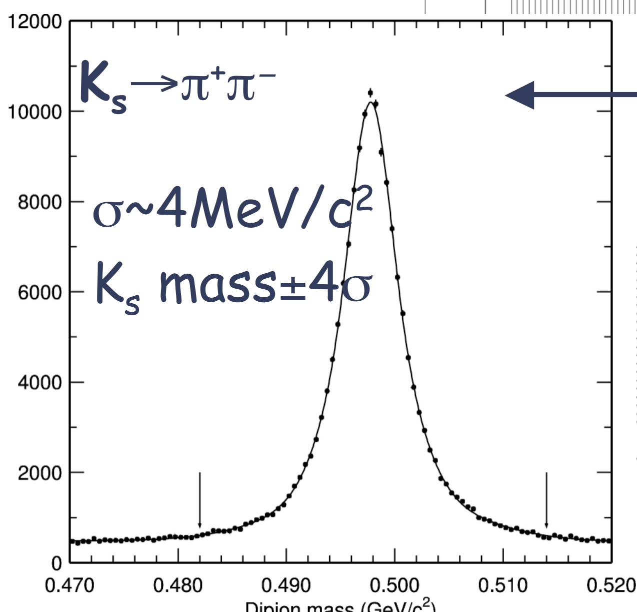
$B^0 \rightarrow J/\psi\ K_s(\rightarrow\pi^+\pi^-)$

"golden mode"





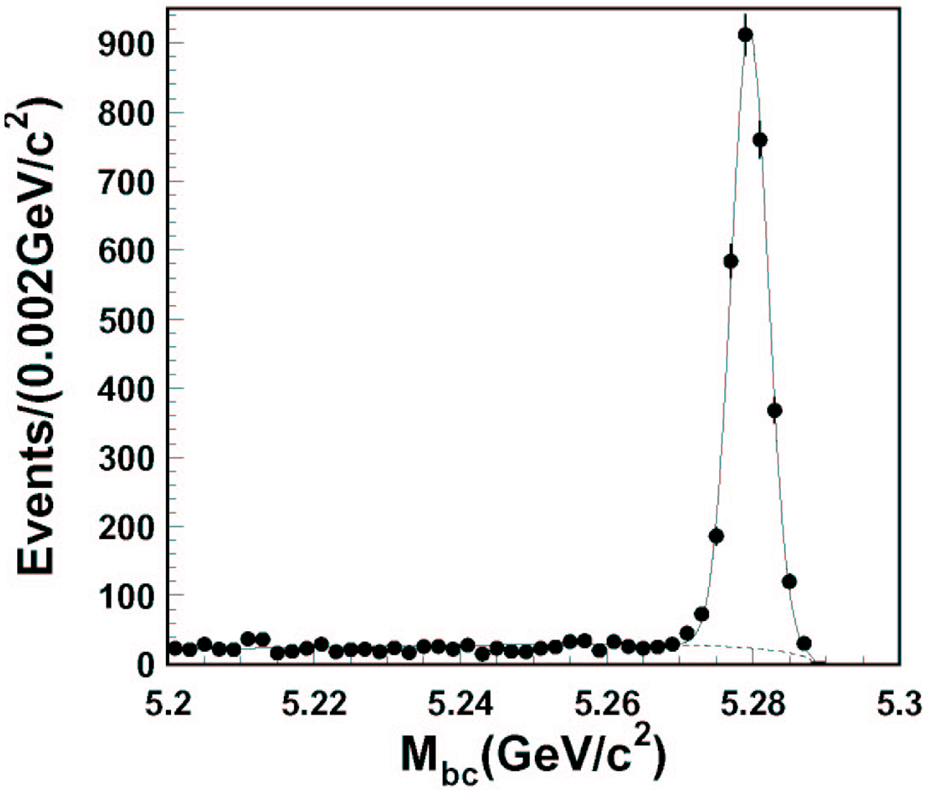
1lepton+1"not-hadron"



BELLE-CONF-0436

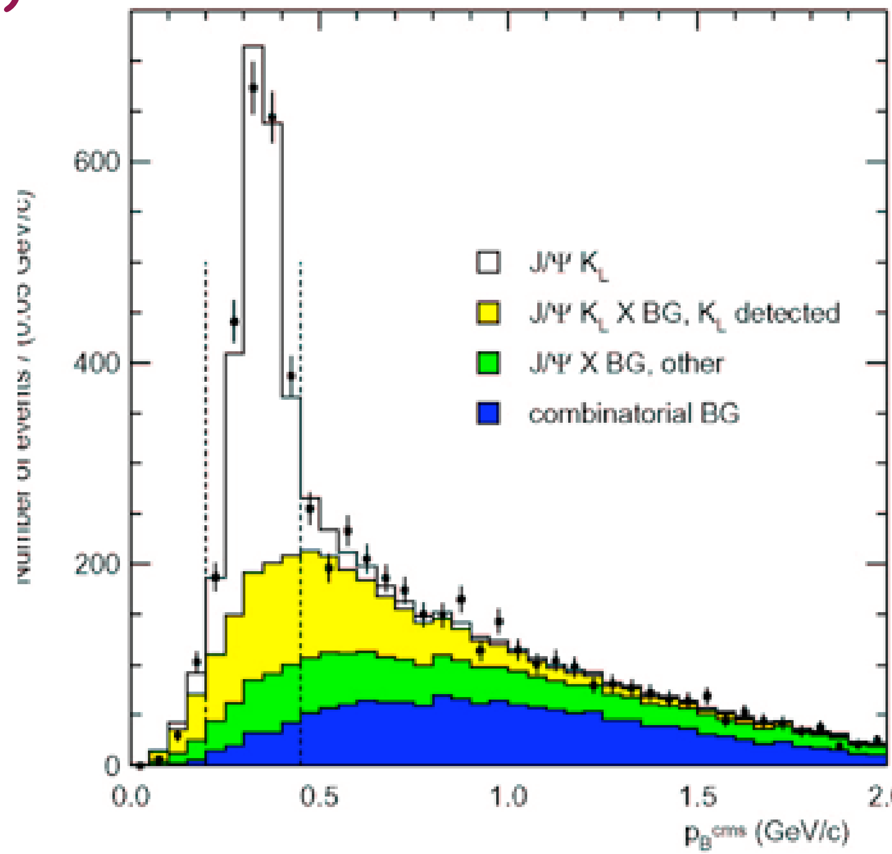
full reconstruction

{charmonium}+K_s tag (CP=−1)



"partial" reconstruction

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



Asymmetry -> sin2ϕ_1

140 fb^{-1}

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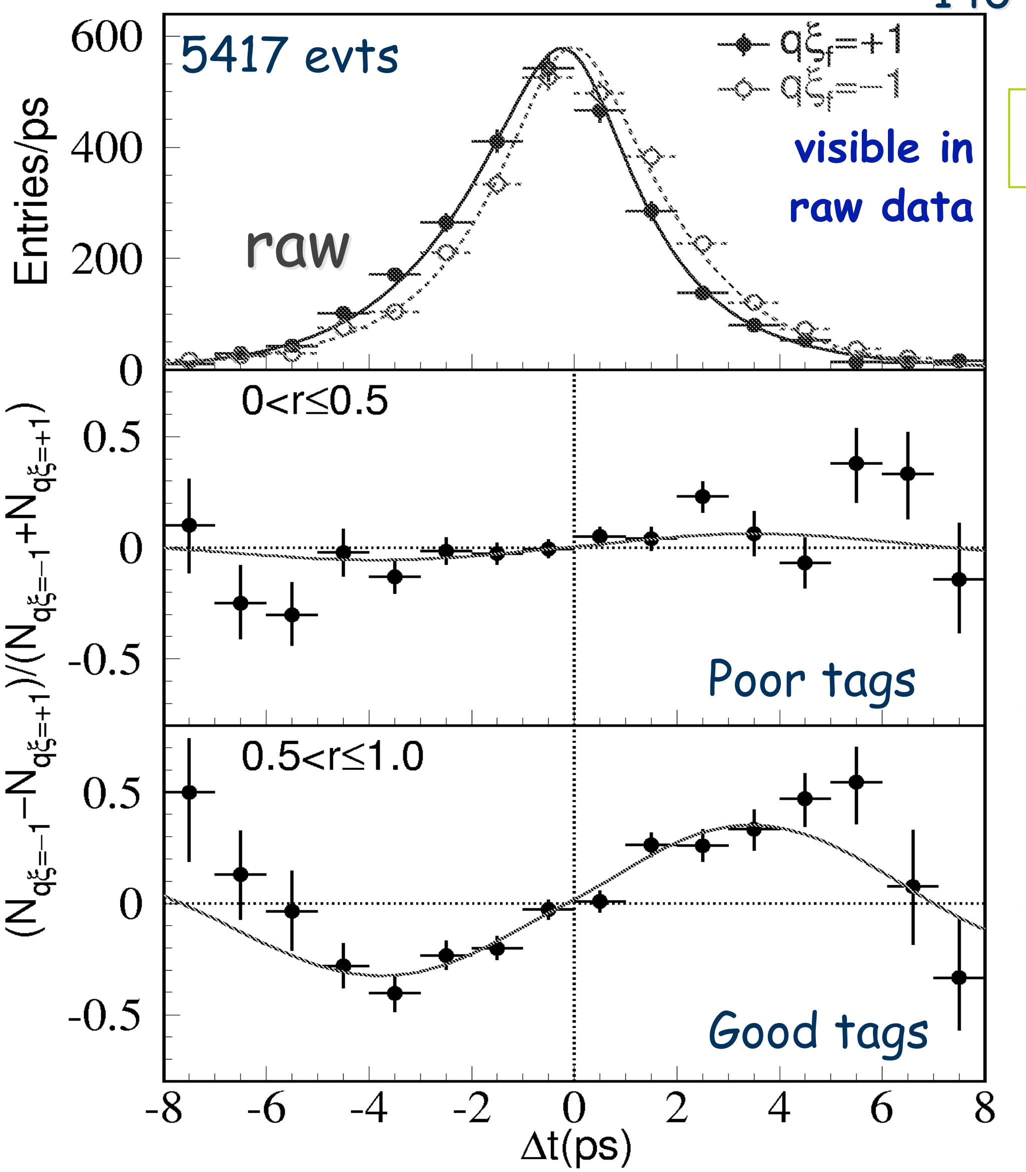
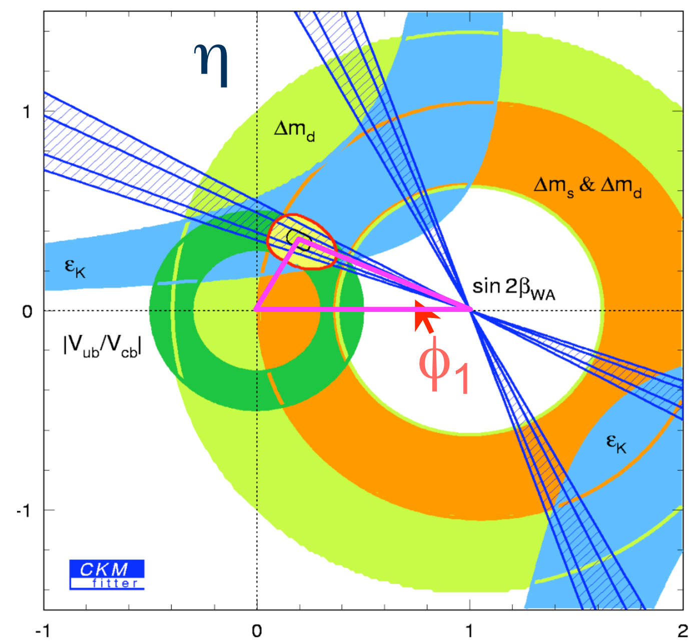


sin2ϕ_1= 0.728±0.056±0.023

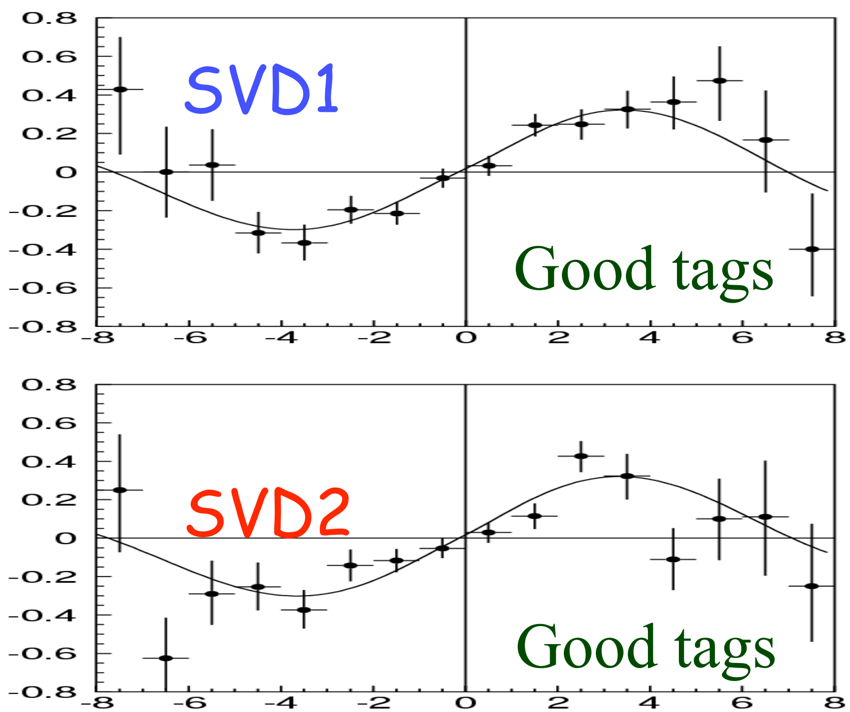
consistent with no direct CP violation



world average:
sin2ϕ_1= 0.726±0.037

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

[hep-ex/0409049]



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

$\mathcal{S} = 0.696 \pm 0.061$ (stat)

$\mathcal{A} = 0.011 \pm 0.043$ (stat)

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

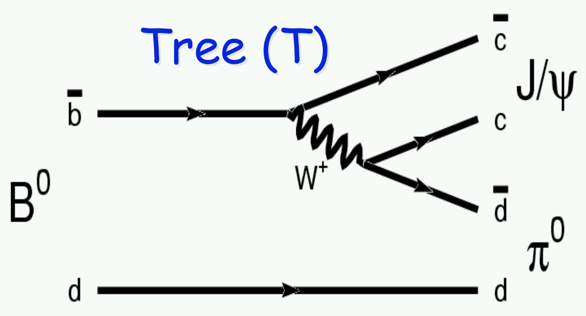
$\mathcal{S} = 0.629 \pm 0.069$ (stat)

$\mathcal{A} = 0.035 \pm 0.044$ (stat)

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

Other paths to CP asymmetry

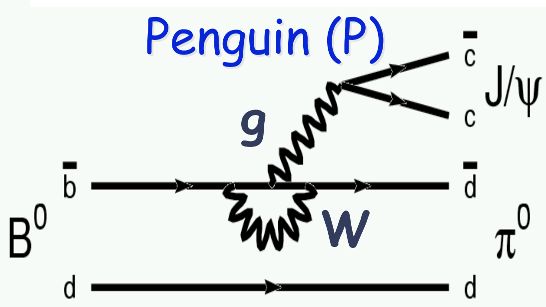
e.g. $B \to J/\psi\pi^0$ 2 processes, different phases, + mixing



$\propto V_{cb}^{*}V_{cd}$

mixing+ "

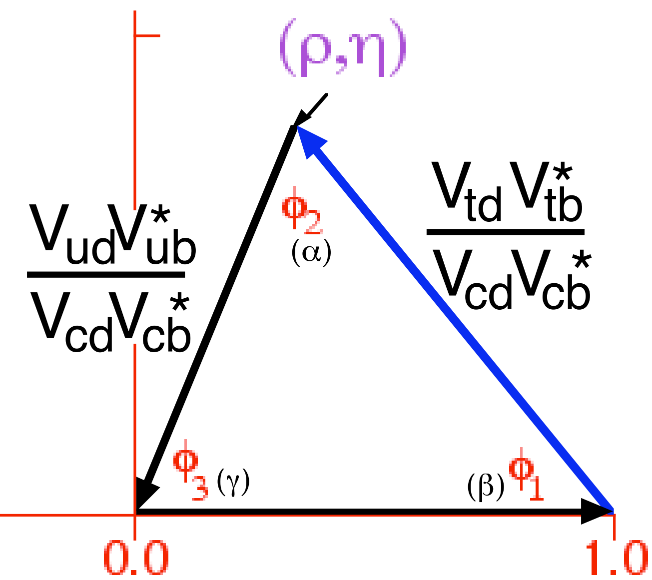
$\propto V_{tb}^{*2}V_{td}^{2}V_{cb}V_{cd}^{*}$



$\propto V_{tb}^{*}V_{td}$

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

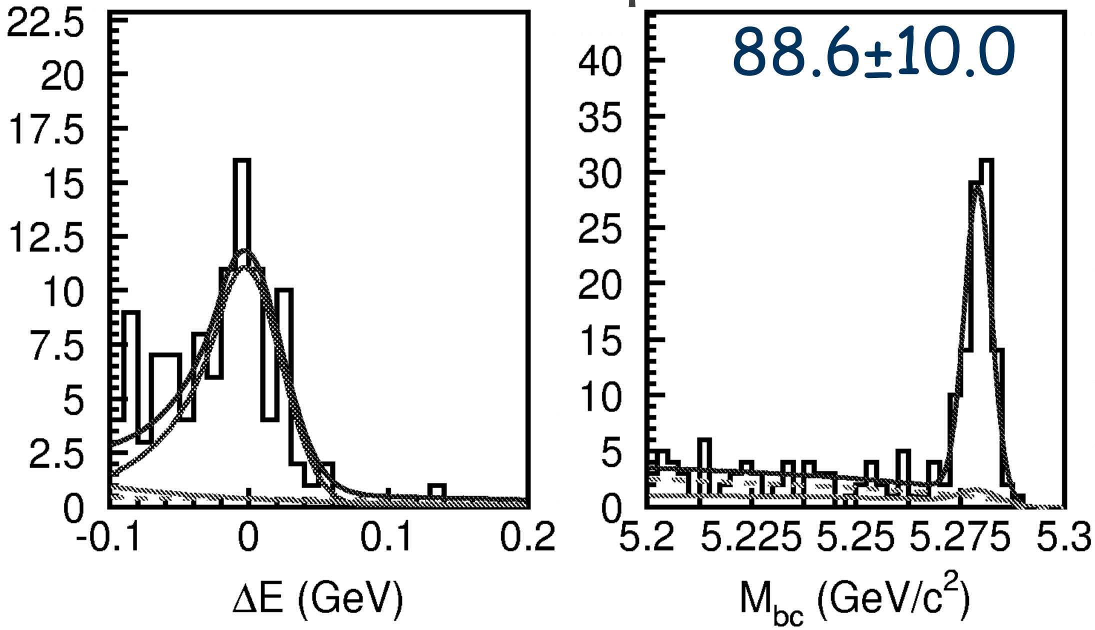
relation to ϕ_1 depends on T/P relative amplitudes, strong phase (not known)

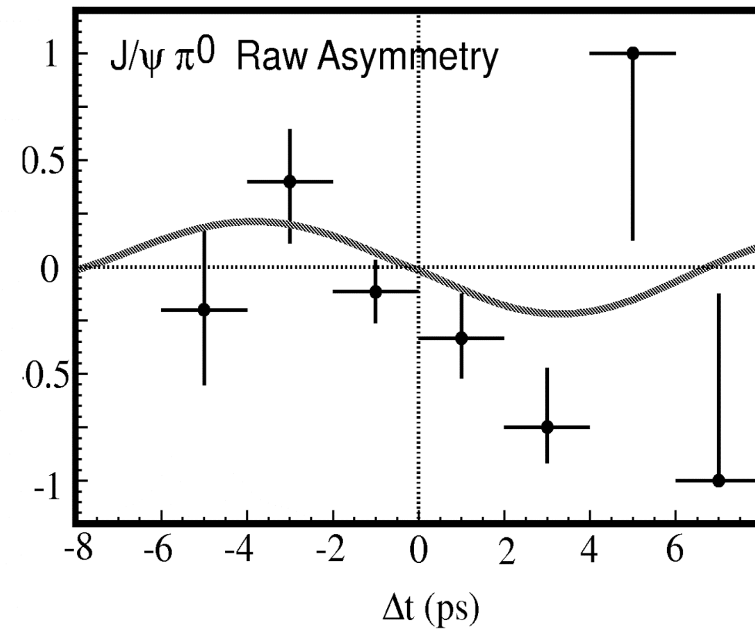
expect S = $-\sin 2\phi_1$ if penguin is small

$b \to \{c\bar{c}d\}$: $B \to J/\psi\ \pi^0$ (CP=+1)

PRL93,260801 (2004)

$B \to J/\psi\ \pi^0$ 140 fb^{-1}





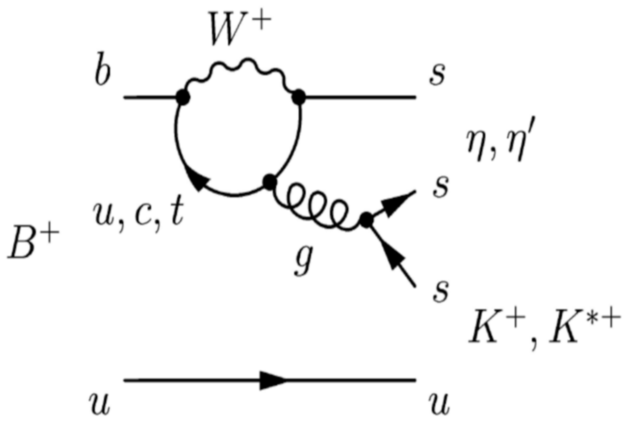
$S = -0.72 \pm 0.42 \pm 0.09$

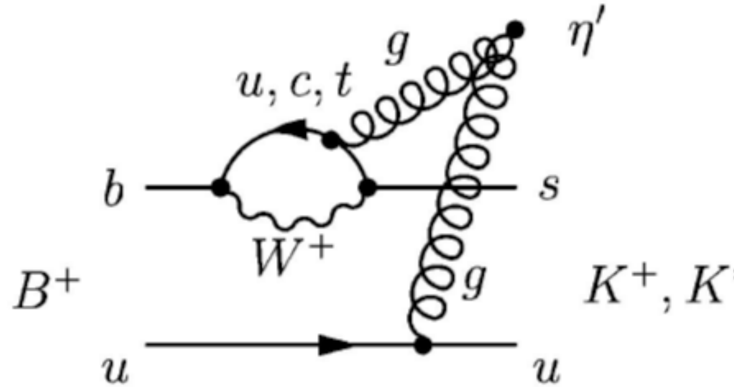
$A = -0.01 \pm 0.29 \pm 0.03$

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

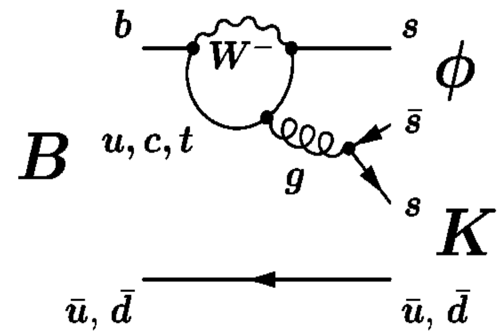
More time-dependent sin2ϕ_1 – or new physics?

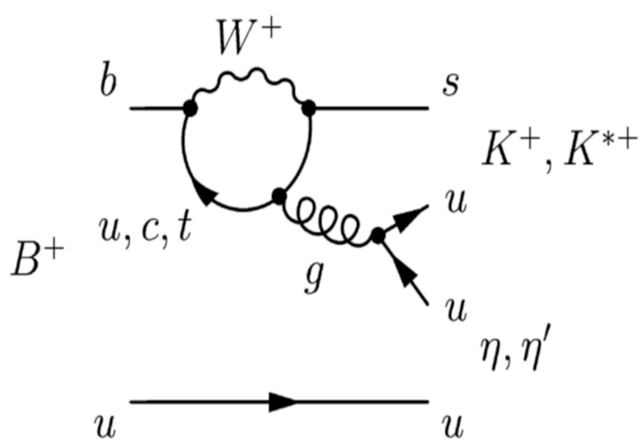
modes dominated by b->s$q\bar{q}$ penguins

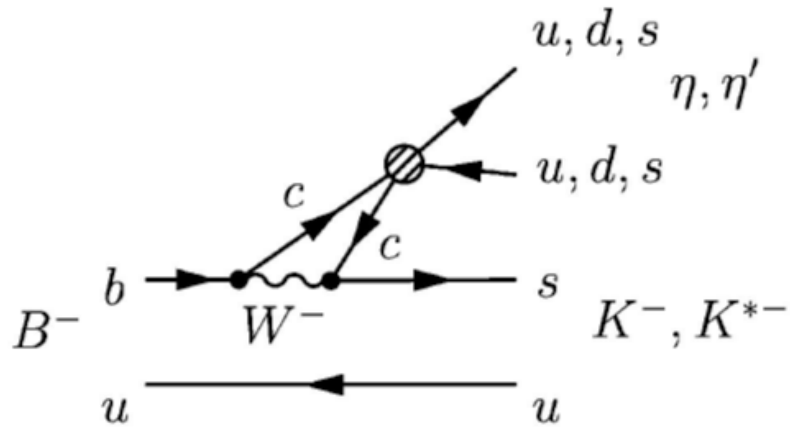




Theoretically cleanest



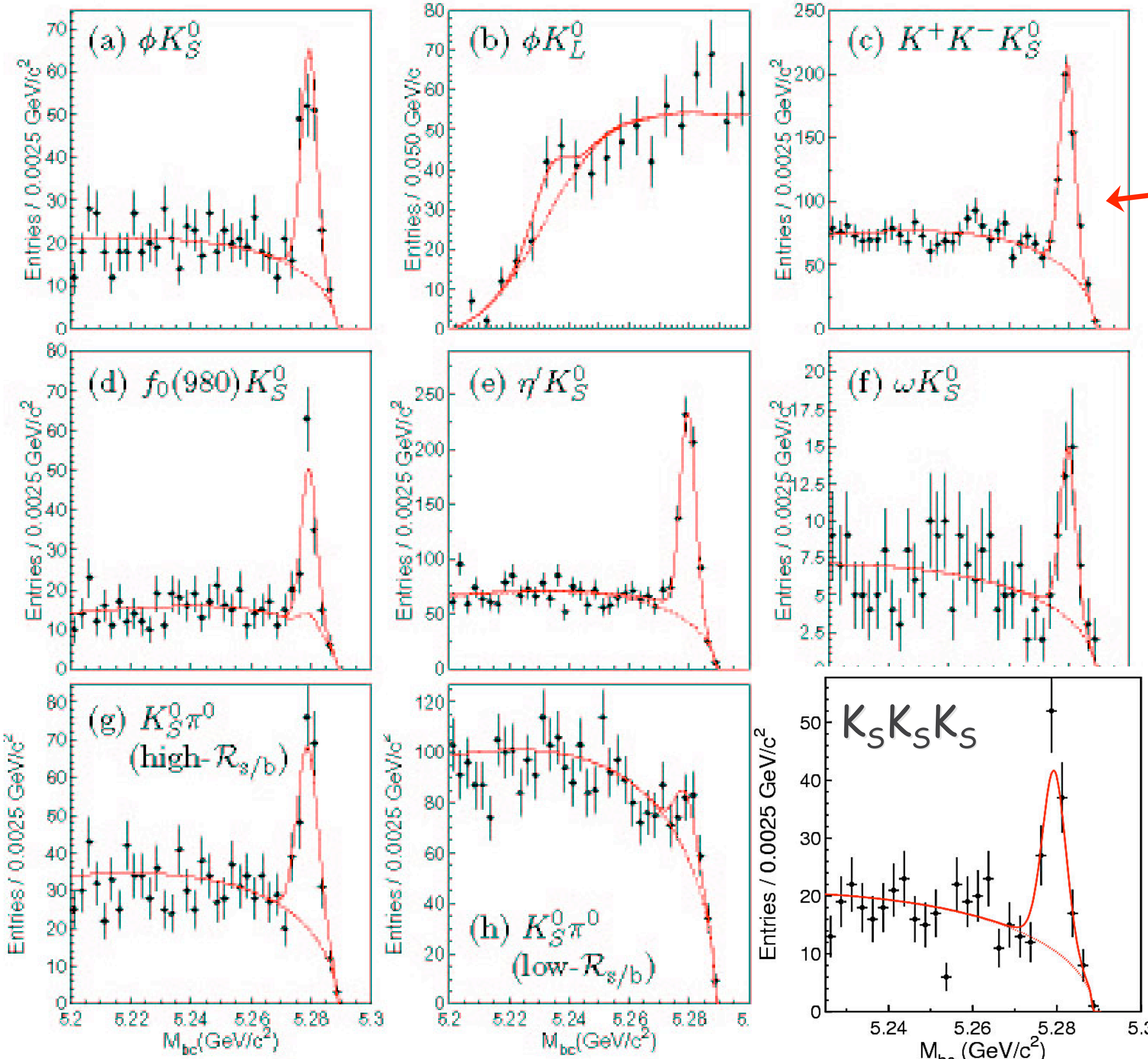




in the absence of New Physics, S = sin2ϕ_1

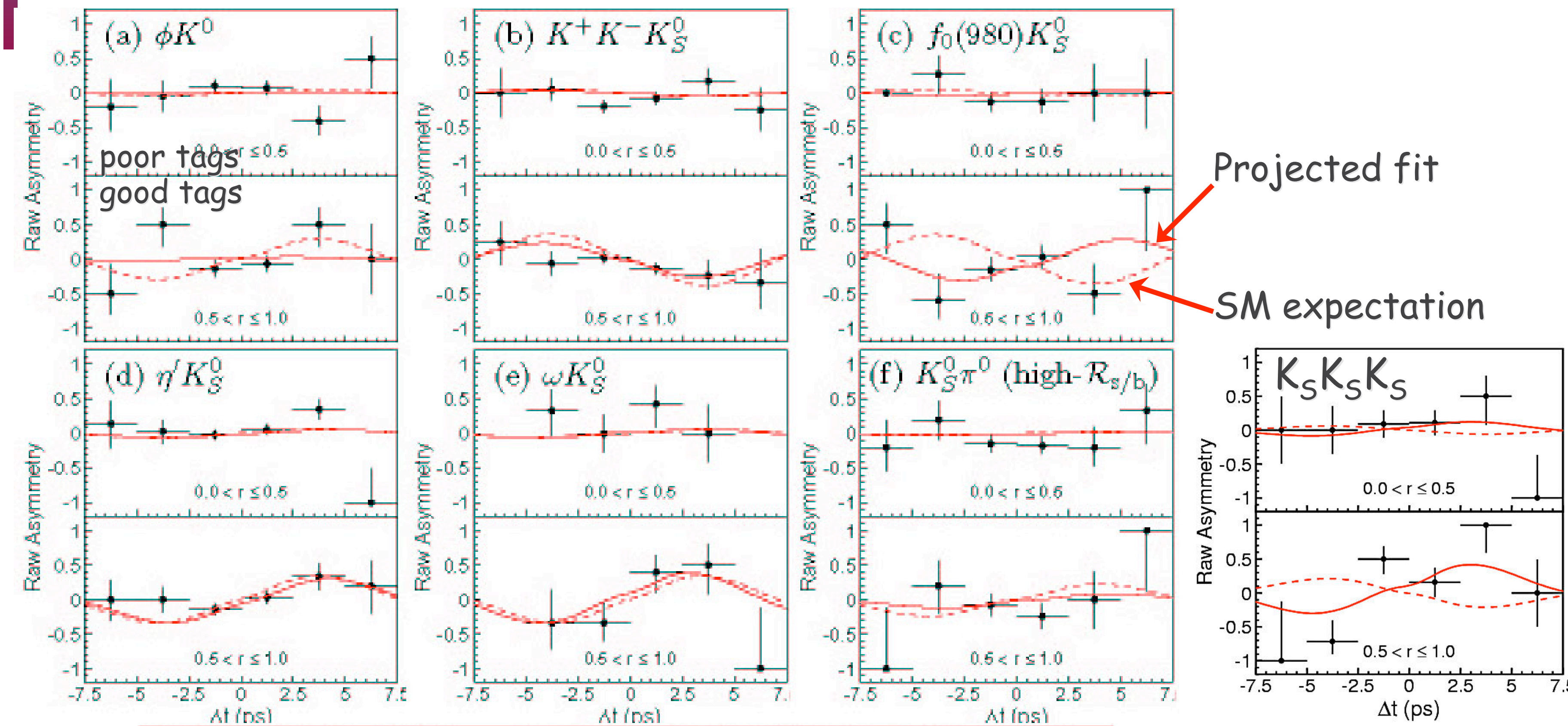
Reconstruction of b->sqq

253 fb^{-1}



CP = +1 (angular analysis)

Time-dependence:



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 $\sin 2\phi_1$ from *b->s* penguins

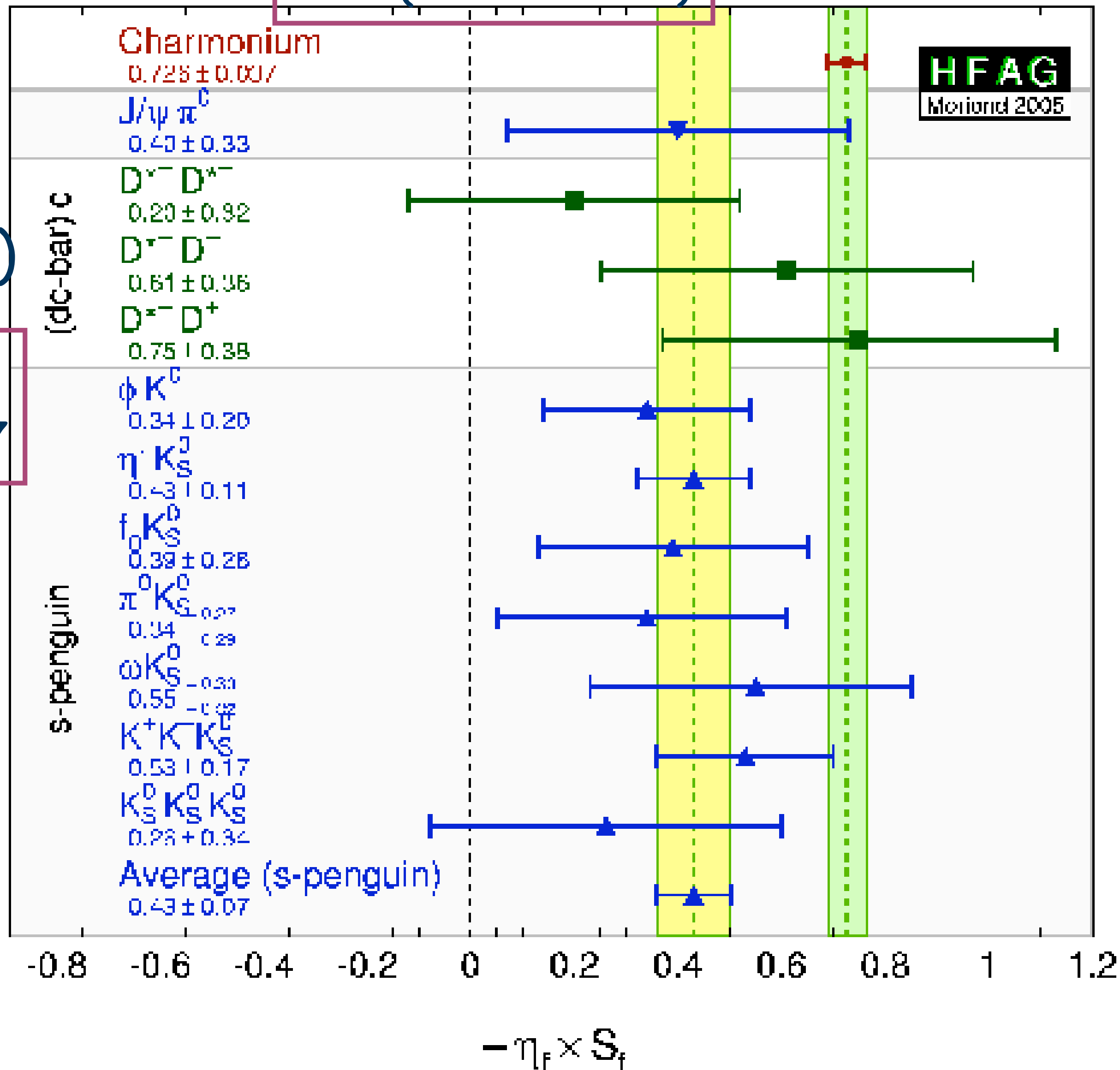
WA (Moriond05.)

$\sin 2\phi_1(b \to s q\bar{q})$ =
- 0.39 ± 0.11 (Belle)
- 0.45 ± 0.09 (*BABAR*)

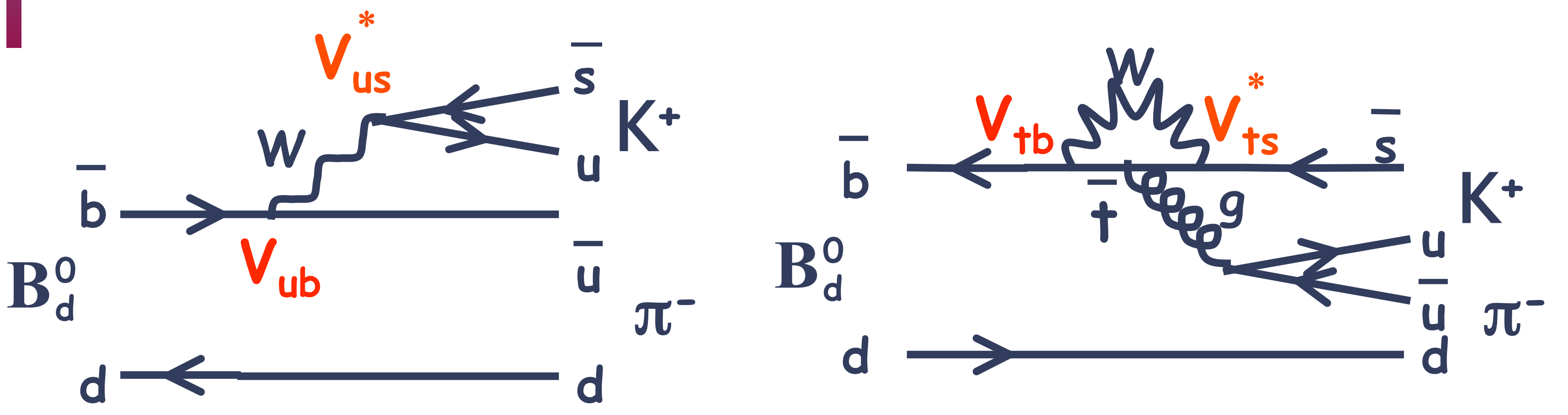
World Average (WA)
$\sin 2\phi_1(b \to s q\bar{q})$= 0.43 ± 0.07

Compare with $c\bar{c}s$:
$\sin 2\phi_1(b \to c\bar{c}s)$
= 0.726 ± 0.037

$CL = 2.1\times10^{-4}$ (3.7σ)



$B^0 \rightarrow K\pi$



Tree-penguin interference -> direct CP violation

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

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

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

275M $B\bar{B}$

[PRL 93, 191802 (2004)]

signal: 2139 ± 53

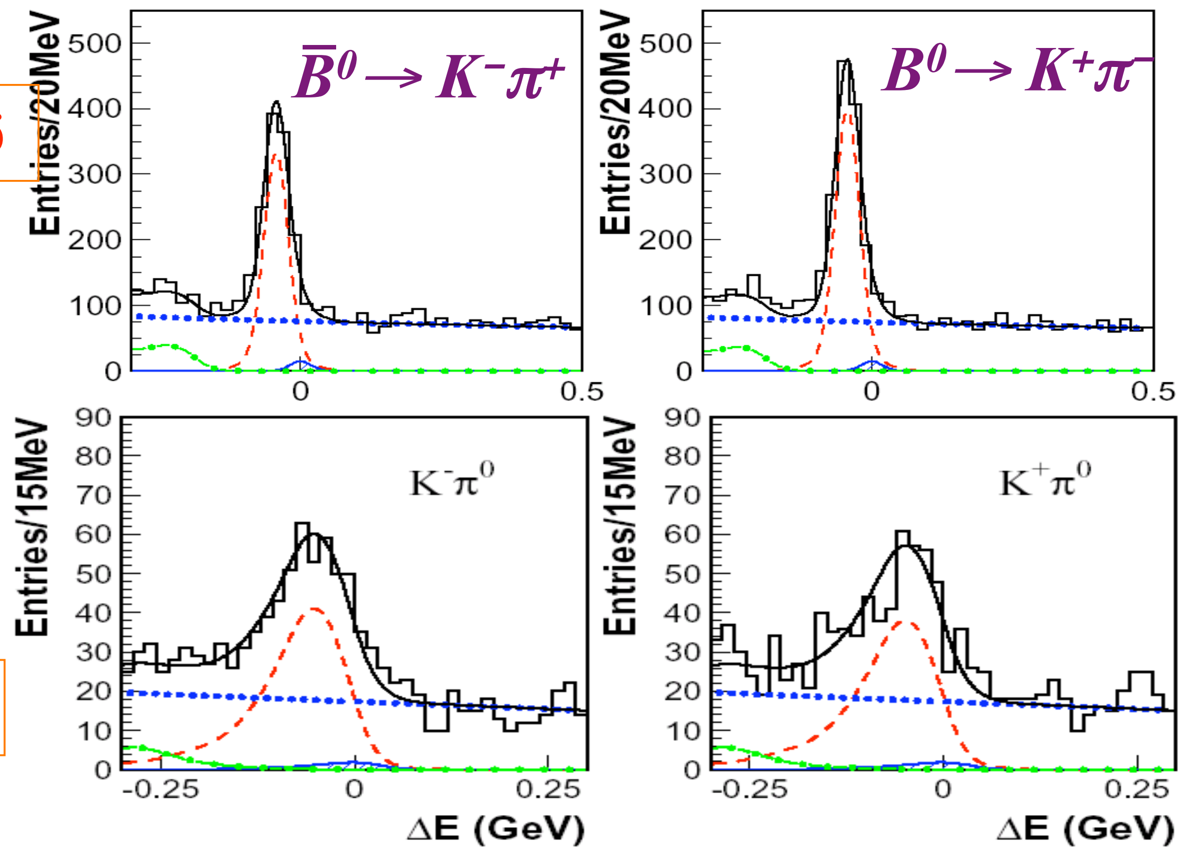
A_{CP}=-0.101±0.025±0.005

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* $1.52\times10^{34}cm^{-2}s^{-1}$ (design: 1×10^{34}); >350M B pairs
- $\sin2\phi_1$ via $\psi K^{(*)0}$ is now a "precision" measurement
- alternative probes of $\sin2\phi_1$– sensitive to new physics
  - $B \to J/\psi\pi^0$ - penguin may be small (need more data)
  - penguin-dominated $B \to sq\bar{q}$ - suggestive!
- 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 (450) fb^{-1} by summer
- Luminosity > design
- the CP challenge: heating up - stay tuned!