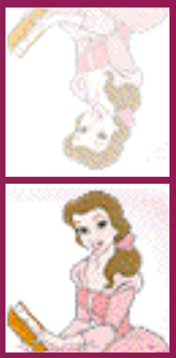
Univertsity of Michigan HEP seminar, April 19, 2004

Reflections on Beauty: CP Asymmetries at Belle



- Weak interaction: CP, CKM matrix
- B(eauty) mesons & CP asymmetry
- B production: e^+e^- -> (4S) at KEKB
- Belle experiment
  - Highlights in CP
  - Selected results
- Plans

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Belle Collaboration

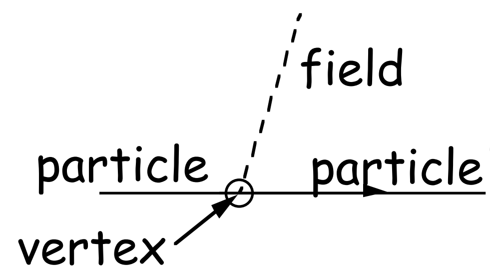
Symmetry of Physical Laws

In an interaction-free universe (relativistic QM)

- massless particles
- symmetric in transformations
  P(r<—>-r), C(particle<—> antiparticle), T(t<—>-t)

Add interactions: emission/absorption of field quantum

- vertex contains
  symmetry (or asymmetry) info
  interaction strength/probability
  µ ("charge" g)^2 µ "coupling constant"
- mass ≠ 0 via self-interaction



Forces: Strong, Electromagnetic, **Weak**, Gravitational

coupling ~ 10^{-5}, quanta $W^{\pm}$, Z^0

Weak interaction

- the only known force that
  - allows particle to change identity (flavor)
  - violates P symmetry (maximally)

    right-handed particles, left-handed antiparticles.

    (no coupling to LH particles, RH antiparticles)

  … but preserves CP symmetry (mostly)
  - small CP asymmetry

    .. but to y2k, seen only in K_L (1963)

Hadronic modes, including Charge conjugation×Parity Violating (*CPV*) modes

Γ_9	$3\pi^0$		(21.11 ± 0.23) %
Γ_{10}	$\pi^+\pi^-\pi^0$		(12.57 ± 0.19) %
Γ_{11}	$\pi^+\pi^-$	*CPV*	$(2.081 \pm 0.026) \times 10^{-3}$
Γ_{12}	$\pi^0\pi^0$	*CPV*	$(9.40 \pm 0.13) \times 10^{-4}$

CP Violation

Why is it of interest?

- matter-antimatter asymmetry in universe requires CP-violating interactions (Sakharov 1967)

What is source of CP asymmetry in K_L? in universe?

- … a possible clue in weak coupling strengths…

Weak coupling strengths

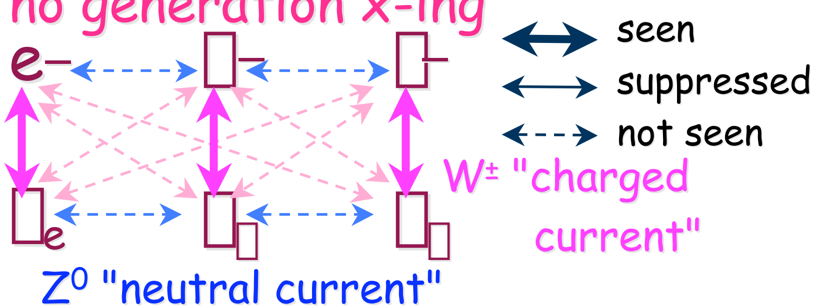
Standard Model = 12 fermion flavors (+antifermion)

- 3 generations(distinguished only by mass)x2 typesx2 ea(strong & EM couplings)
- stable, but for weak interaction

		Generation		
type	Q/|e|	1	2	3
lepton (no strong)	-1 0	e ν_e	μ ν_μ	τ ν_τ
quark (strong)	+2/3 -1/3	up down	Charm Strange	truth beauty

weak couplings:

- leptons: ~universal, 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

- charged-current interaction ~ $g_F \times \begin{pmatrix} e^- & \mu^- & \tau^- \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \quad \begin{pmatrix} u & c & t \\ d' & s' & b' \end{pmatrix}$

  no generation x-ing, universal coupling g_F

- quark mass/flavor defined by strong force, perturbed by weak:

  d', s', b'(weak) are linear combinations of d, s, b (strong)

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

$\mathcal{M}$ — Cabibbo-Kobayashi-Maskawa (CKM) matrix

complex
preserves metric
" orthogonality
} ≡ unitary

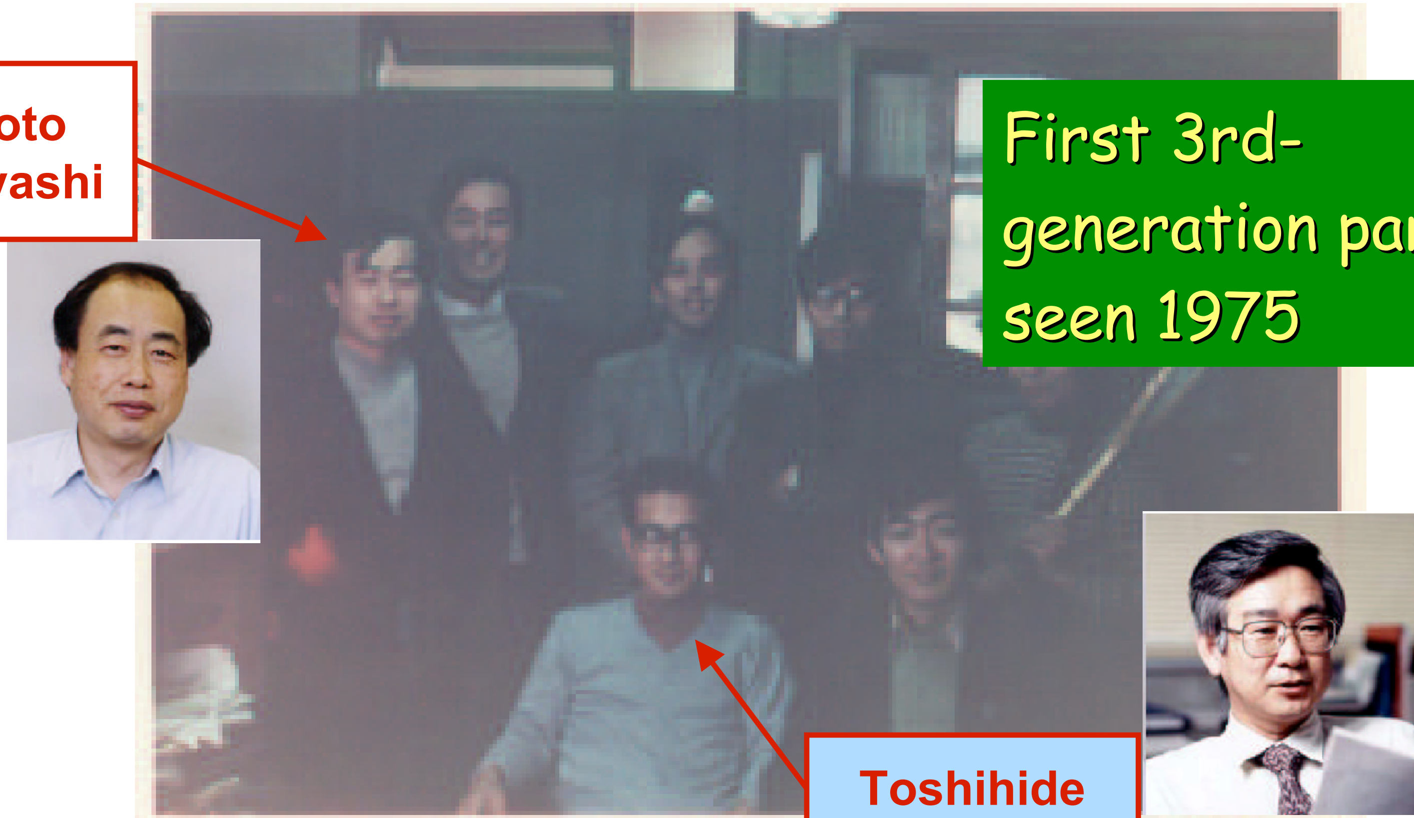
Explains (Glashow-Iliopoulos-Maiani)

- 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 (□) seen 1975

Toshihide Maskawa

3-generation Matrix

$$\{1/g_F \times \text{couplings}\} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{ccc} d & s & b \\ \end{array}\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity →

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1□□^2/2 & □ & □^3A(□□i□) \\ □□ & 1□□^2/2 & □^2A \\ □^3A(1□□□i□) & □□^2A & 1 \end{pmatrix}$$

irreducibly complex

from decay rates,

□ = 0.220 ± 0.002

A = 0.81 ± 0.08

|□□i□| = 0.36 ± 0.09

|1□□□i□| = 0.79 ± 0.19

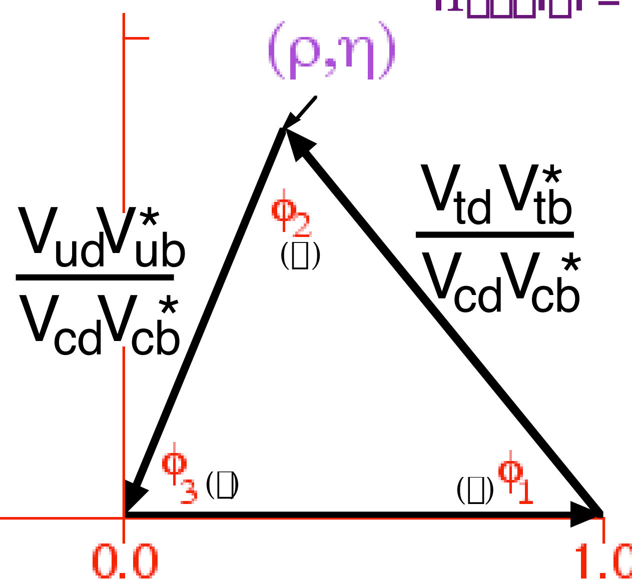
$V_{ji}^* V_{jk} = □_{ik}$

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

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

↓ □(□+□□) ↓ □(1□□□□□)

(□, □): "unitarity triangle"



Self-consistent if CKM is correct

CKM CP phenomenology

CP asymmetry - requires ≥3 generations

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

-> to test, probe different angles w different decays

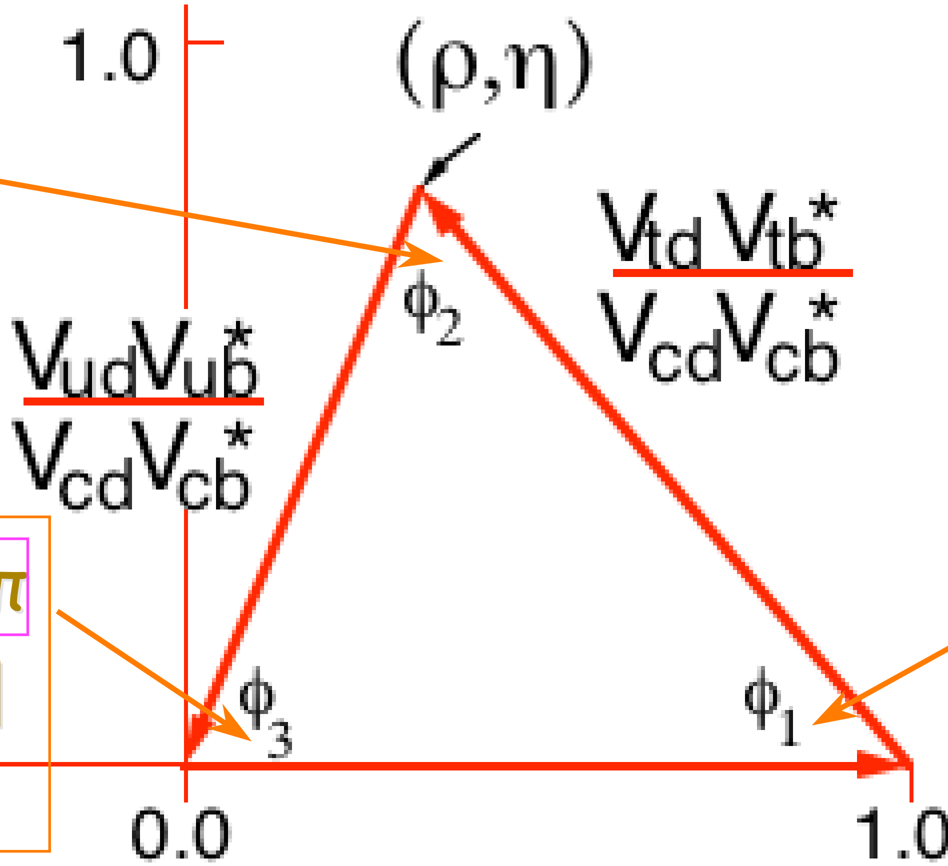
$B^0 \to \pi\pi$

$B^0 \to$ □π

$B^0 \to D^*\pi$

$B^0 \to D^*$□

$B \to D_{CP}K$



B factory program: are all asymmetries consistent w single KM phase?

first result

$B^0 \to J/$□K_s

$B^0 \to$ □K_s

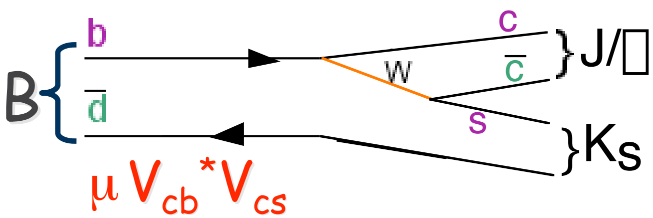
$B^0 \to D^{(*)} D^{(*)}$

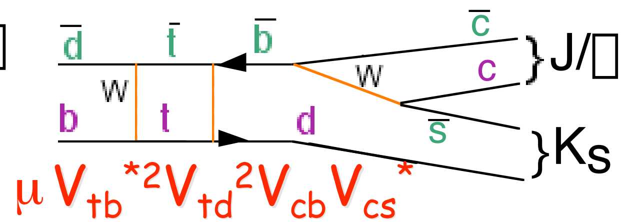
manifestation of complex coupling

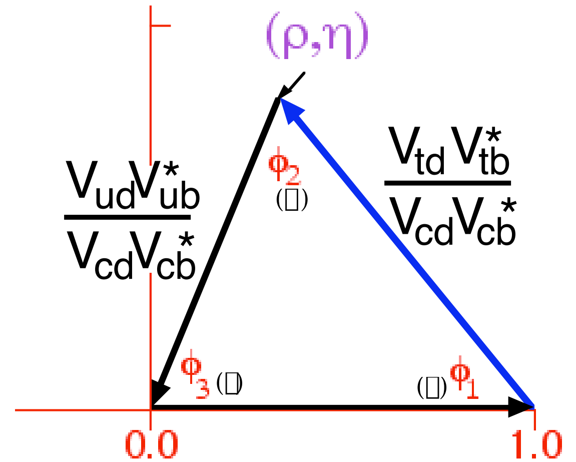
e.g. $B \to J/\psi\ K_s$ for $\sin 2\phi_1$ (Sanda/Bigi/Carter)

"indirect" CP asymmetry

tree (real V_{ij}) + mixing+tree (μV_{td}^{*2})







(no cc of hadronic phase under CP)

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

Bottom line: CP-dependent oscillation in time:

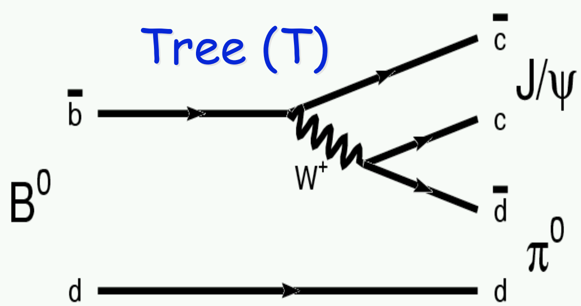
$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b\eta_{CP}\sin 2\phi_1 \sin(\Delta m \Delta t));$$

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

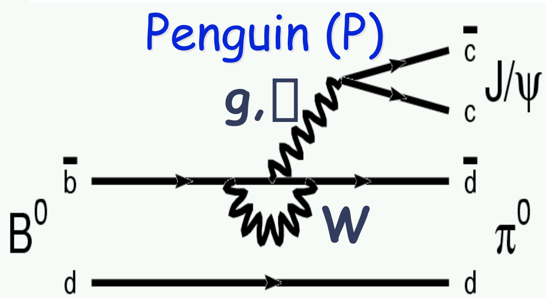
This is only the cleanest, simplest - "golden mode"

CP phenomenology: variation

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



μ $V_{cb}^{*}V_{cd}$



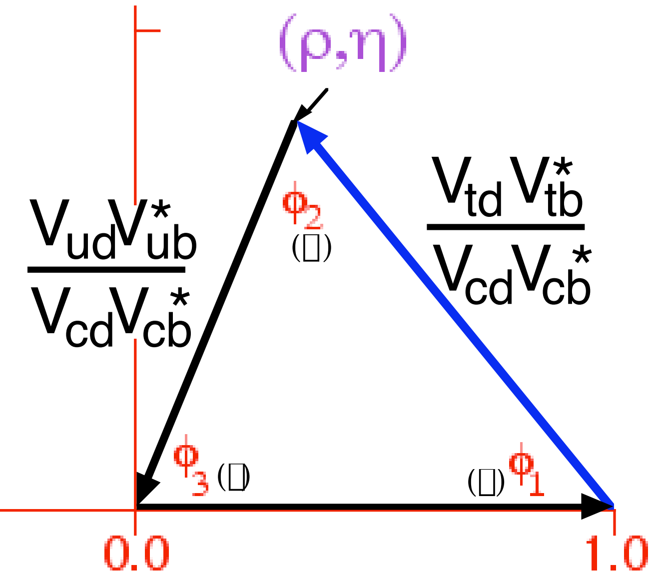
μ $V_{tb}^{*}V_{td}$

mixing+ "

μ $V_{tb}^{*2}V_{td}^{2}V_{cb}V_{cd}^{*}$

mixing+ "

μ $V_{tb}^{*2}V_{td}^{2}V_{tb}V_{td}^{*}$



Bottom line: "direct" CP asymmetry possible

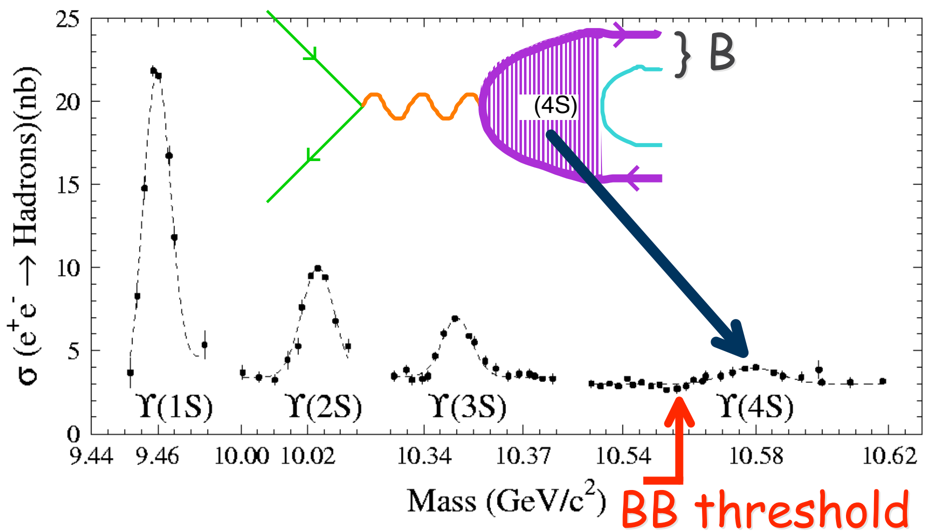
$$q = \begin{pmatrix} +1 \text{if } B_{t=0} = B^0 \\ -1 \text{if } B_{t=0} = \bar{B}^0 \end{pmatrix}$$

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

"direct" asym

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

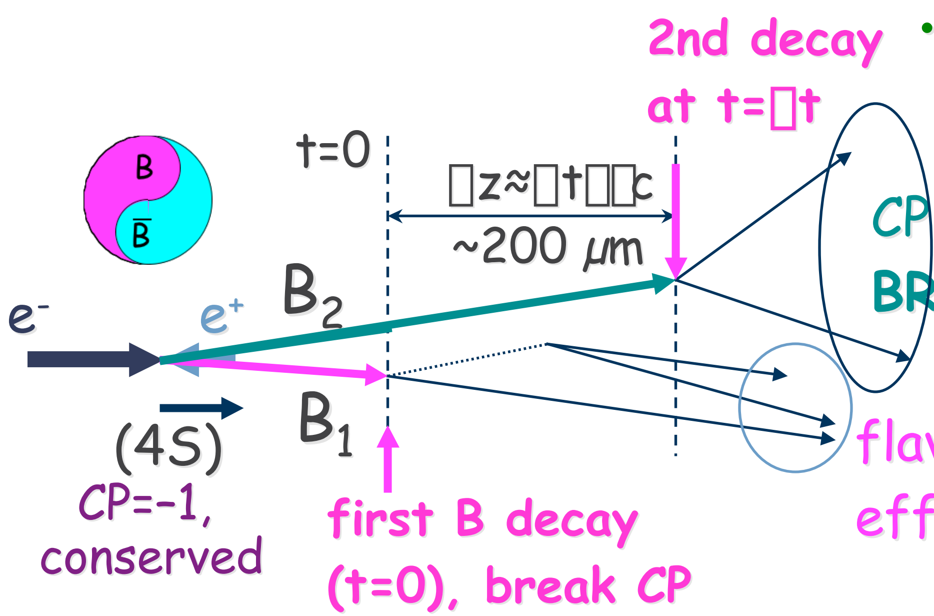
B production: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



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

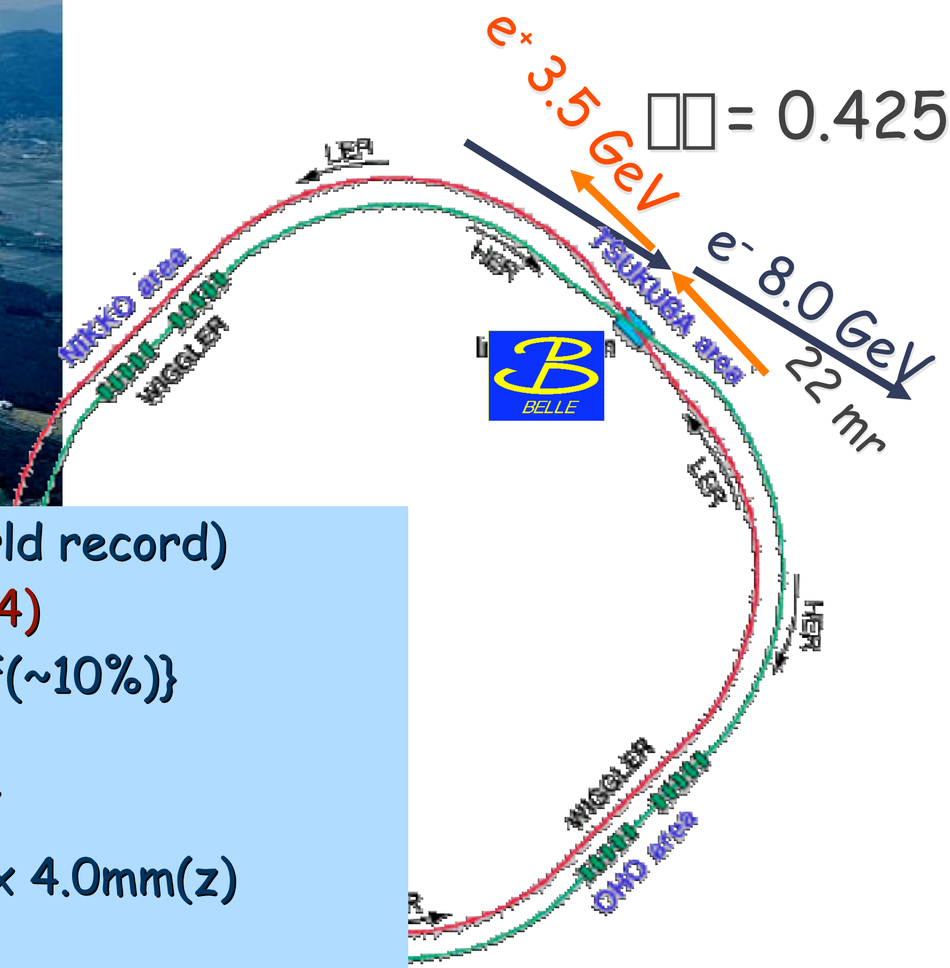
What else is needed?

- $>10^7$ B's just to get started - KEKB
- hadron (K/π) ID - dE/dx, aerogel(Cerenkov), time-of-flight
- lepton ID - CsI, multilayer μ
- <<200μm vertexing – double-sided silicon strip



flavor tag @t=0: e, μ, K±, ...
effective eff ~30%

Colliding beams: KEKB



L_{max} = 1.20 X 10^{34} $cm^{-2}s^{-1}$ (world record)

Data (6/1999–4/2004)

$\int L dt$ = 230 fb^{-1}@{ (4S)+off(~10%)}

(>2.2x10^{8} B events)

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

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

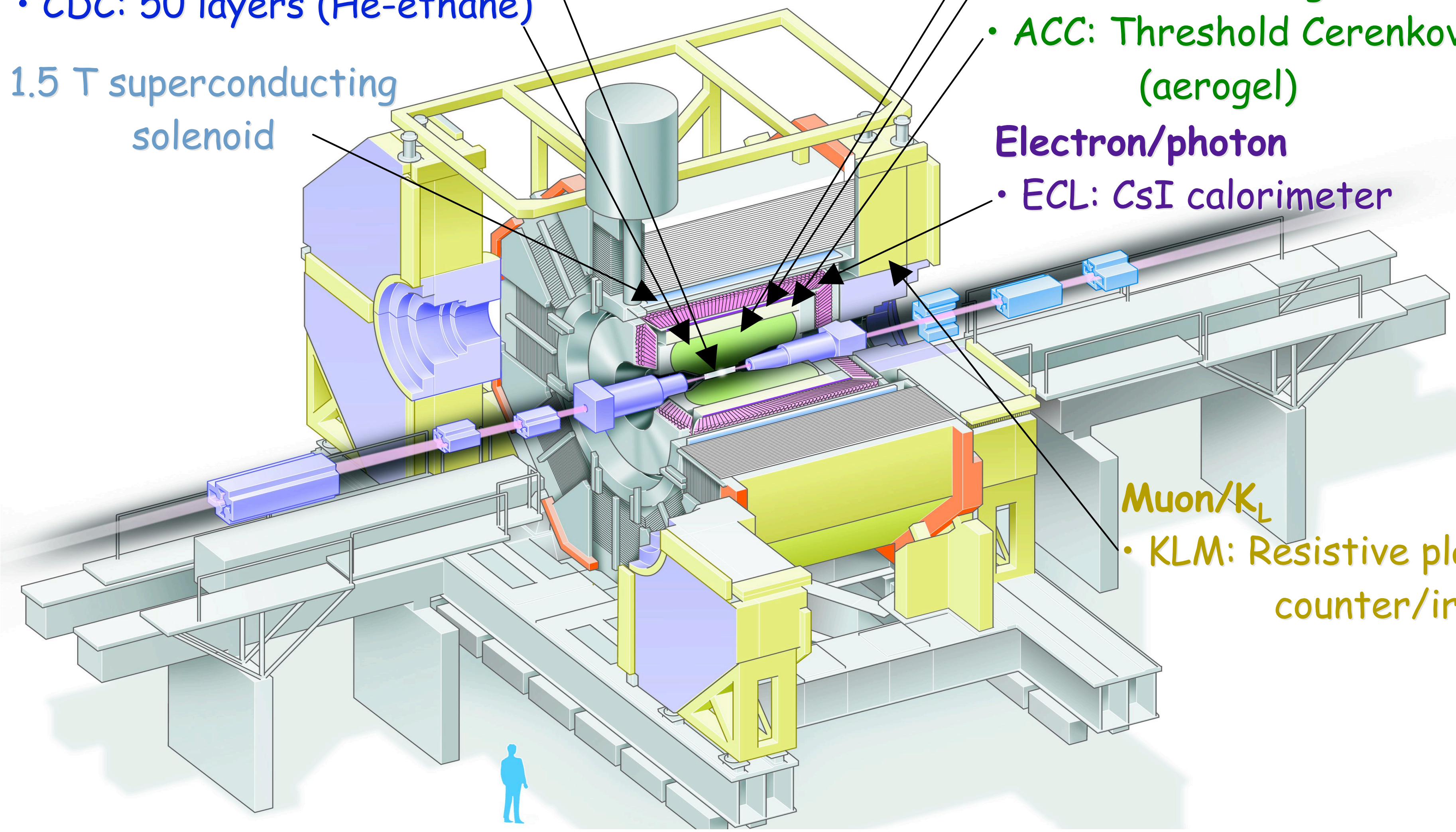
The Detector

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

… not least, the people

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Measurement of the *CP* Violation Parameter $\sin 2\phi_1$ in B_d^0 Meson Decays

A. Abashian,[44] K. Abe,[8] K. Abe,[36] I. Adachi,[8] Byoung Sup Ahn,[14] H. Aihara,[37] M. Akatsu,[19] G. Alimonti,[7] K. Aoki,[8] K. Asai,[20] M. Asai,[9] Y. Asano,[42] T. Aso,[41] V. Aulchenko,[2] T. Aushev,[12] A. M. Bakich,[33] E. Banas,[15] S. Behari,[8] P. K. Behera,[43] D. Beiline,[2] A. Bondar,[2] A. Bozek,[15] T. E. Browder,[7] B. C. K. Casey,[7] P. Chang,[23] Y. Chao,[23] B. G. Cheon,[32] S.-K. Choi,[6] Y. Choi,[32] Y. Doi,[8] J. Dragic,[17] A. Drutskoy,[12] S. Eidelman,[2] Y. Enari,[19] R. Enomoto,[8,10] C. W. Everton,[17] F. Fang,[7] H. Fujii,[8] K. Fujimoto,[19] Y. Fujita,[8] C. Fukunaga,[39] M. Fukushima,[10] A. Garmash,[2,8] A. Gordon,[17] K. Gotow,[44] H. Guler,[7] R. Guo,[21] J. Haba,[8] T. Haji,[37] H. Hamasaki,[8] K. Hanagaki,[29] F. Handa,[36] K. Hara,[27] T. Hara,[27] T. Haruyama,[8] N. C. Hastings,[17] K. Hayashi,[8] H. Hayashii,[20] M. Hazumi,[27] E. M. Heenan,[17] Y. Higashi,[8] Y. Higashino,[19] I. Higuchi,[36] T. Higuchi,[37] T. Hirai,[38] H. Hirano,[40] M. Hirose,[19] T. Hojo,[27] Y. Hoshi,[35] K. Hoshina,[40] W.-S. Hou,[23] S.-C. Hsu,[23] H.-C. Huang,[23] Y.-C. Huang,[21] S. Ichizawa,[38] Y. Igarashi,[8] T. Iijima,[8] H. Ikeda,[8] K. Ikeda,[20] K. Inami,[19] Y. Inoue,[26] A. Ishikawa,[19] H. Ishino,[38] R. Itoh,[8] G. Iwai,[25] M. Iwai,[8] M. Iwamoto,[3] H. Iwasaki,[8] Y. Iwasaki,[8] D. J. Jackson,[27] P. Jalocha,[15] H. K. Jang,[31] M. Jones,[7] R. Kagan,[12] H. Kakuno,[38] J. Kaneko,[38] J. H. Kang,[45] J. S. Kang,[14] P. Kapusta,[15] K. Kasami,[8] N. Katayama,[8] H. Kawai,[3] H. Kawai,[37] M. Kawai,[8] N. Kawamura,[1] T. Kawasaki,[25] H. Kichimi,[8] D. W. Kim,[32] Heejong Kim,[45] H. J. Kim,[45] Hyunwoo Kim,[14] S. K. Kim,[31] K. Kinoshita,[5] S. Kobayashi,[30] S. Koike,[8] S. Koishi,[38] Y. Kondo,[8] H. Konishi,[40] K. Korotushenko,[29] P. Krokovny,[2] R. Kulasiri,[5] S. Kumar,[28] T. Kuniya,[30] E. Kurihara,[3] A. Kuzmin,[2] Y.-J. Kwon,[45] M. H. Lee,[8] S. H. Lee,[31] C. Leonidopoulos,[29] H.-B. Li,[11] R.-S. Lu,[23] Y. Makida,[8] A. Manabe,[8] D. Marlow,[29] T. Matsubara,[37] T. Matsuda,[8] S. Matsui,[19] S. Matsumoto,[4] T. Matsumoto,[19] Y. Mikami,[36] K. Misono,[19] K. Miyabayashi,[20] H. Miyake,[27] H. Miyata,[25] L. C. Moffitt,[17] A. Mohapatra,[43] G. R. Moloney,[17] G. F. Moorhead,[17] N. Morgan,[44] S. Mori,[42] T. Mori,[4] A. Murakami,[30] T. Nagamine,[36] Y. Nagasaka,[18] Y. Nagashima,[27] T. Nakadaira,[37] T. Nakamura,[38] E. Nakano,[26] M. Nakao,[8] H. Nakazawa,[4] J. W. Nam,[32] S. Narita,[36] Z. Natkaniec,[15] K. Neichi,[35] S. Nishida,[16] O. Nitoh,[40] S. Noguchi,[20] T. Nozaki,[8] S. Ogawa,[34] T. Ohshima,[19] Y. Ohshima,[38] T. Okabe,[19] T. Okazaki,[20] S. Okuno,[13] S. L. Olsen,[7] W. Ostrowicz,[15] H. Ozaki,[8] P. Pakhlov,[12] H. Palka,[15] C. S. Park,[31] C. W. Park,[14] H. Park,[14] L. S. Peak,[33] M. Peters,[7] L. E. Piilonen,[44] E. Prebys,[29] J. L. Rodriguez,[7] N. Root,[2] M. Rozanska,[15] K. Rybicki,[15] J. Ryuko,[27] H. Sagawa,[8] S. Saitoh,[3] Y. Sakai,[8] H. Sakamoto,[16] H. Sakaue,[26] M. Satapathy,[43] N. Sato,[8] A. Satpathy,[8,5] S. Schrenk,[5] S. Semenov,[12] Y. Settai,[4] M. E. Sevior,[17] H. Shibuya,[34] B. Shwartz,[2] A. Sidorov,[2] V. Sidorov,[2] J. B. Singh,[28] S. Stanič,[42] A. Sugi,[19] A. Sugiyama,[19] K. Sumisawa,[27] T. Sumiyoshi,[8] J. Suzuki,[8] J.-I. Suzuki,[8] K. Suzuki,[3] S. Suzuki,[19] S. Y. Suzuki,[8] S. K. Swain,[7] H. Tajima,[37] T. Takahashi,[26] F. Takasaki,[8] M. Takita,[27] K. Tamai,[8] N. Tamura,[25] J. Tanaka,[37] M. Tanaka,[8] Y. Tanaka,[18] G. N. Taylor,[17] Y. Teramoto,[26] M. Tomoto,[19] T. Tomura,[37] S. N. Tovey,[17] K. Trabelsi,[7] T. Tsuboyama,[8] Y. Tsujita,[42] T. Tsukamoto,[8] T. Tsukamoto,[30] S. Uehara,[8] K. Ueno,[23] N. Ujiie,[8] Y. Unno,[3] S. Uno,[8] Y. Ushiroda,[16] Y. Usov,[2] S. E. Vahsen,[29] G. Varner,[7] K. E. Varvell,[33] C. C. Wang,[23] C. H. Wang,[22] M.-Z. Wang,[23] T. J. Wang,[11] Y. Watanabe,[38] E. Won,[31] B. D. Yabsley,[8] Y. Yamada,[8] M. Yamaga,[36] A. Yamaguchi,[36] H. Yamaguchi,[8] H. Yamamoto,[7] T. Yamanaka,[27] H. Yamaoka,[8] Y. Yamaoka,[8] Y. Yamashita,[24] M. Yamauchi,[8] S. Yanaka,[38] M. Yokoyama,[37] K. Yoshida,[19] Y. Yusa,[36] H. Yuta,[1] C. C. Zhang,[11] H. W. Zhao,[8] J. Zhang,[42] Y. Zheng,[7] V. Zhilich,[2] and D. Žontar[42]

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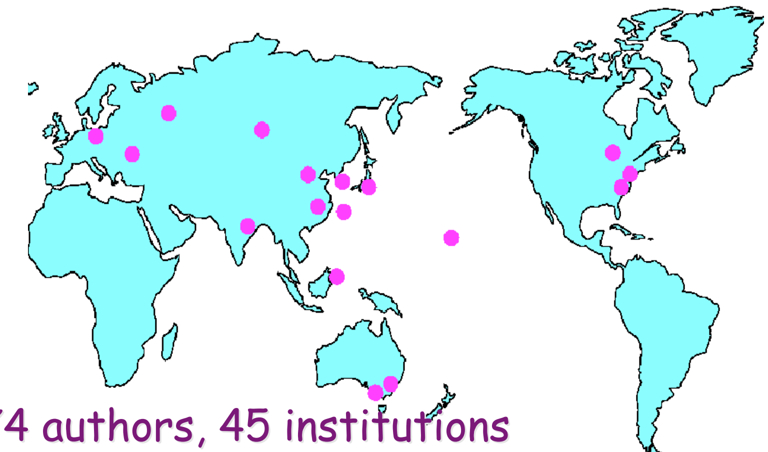

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We present a measurement of the standard model *CP* violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a 10.5 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. One neutral B meson is reconstructed in the $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, or $J/\psi \pi^0$ *CP*-eigenstate decay channel and the flavor of the accompanying B meson is identified from its charged particle decay products. From the asymmetry in the distribution of the time interval between the two B-meson decay points, we determine $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}(\mathrm{stat})^{+0.09}_{-0.10}(\mathrm{syst})$.

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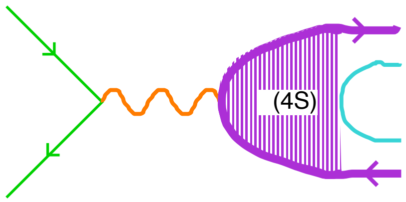
many nations

(numbers vary, every paper)

Belle physics results

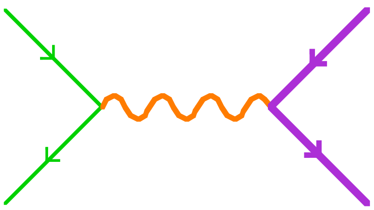
78±2 papers published or in press (1st in 3/2001)

54 abstracts submitted to XXI Lepton-Photon (Fermilab 2003)

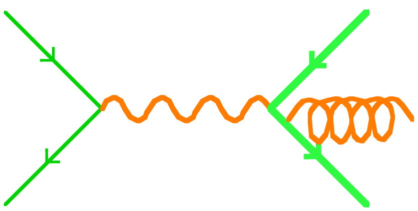


18 - CP asymmetry in B decay

25 - B decay non-CP

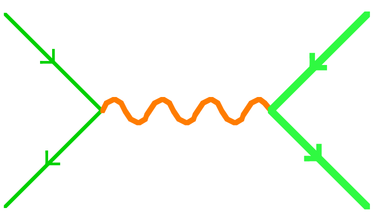


8 - charm hadrons



1 - QCD

Physics topics overlap in many analyses, e.g., discovery of new charmonium states in B decays.



2 - tau

Recent highlights in CP

Beauty: CP and related

- time-dependent CP measurements
  - update of $J/\square K_s$ ($\square_1$)
  - with $J/\square\pi^0$(~$\square_1$), $D^{*+}\pi^-$($2\square_1+\square_3$), $\square K_s$($\square_1$), $\pi^+\pi^-$(~$\square_2$)
- evidence/observation
  - B-> $K^*l^+l^-$, $\pi^0\pi^0$, D^+D^-, $\pi^0\square^0$
- new method for $\square_3$: Dalitz plot analysis
  - D^0K^+ {$D^0 \to K_s\pi^+\pi^-$}

Charm:

- difference of CP lifetimes in D (y_{CP})

time-dependent CP analysis: overview

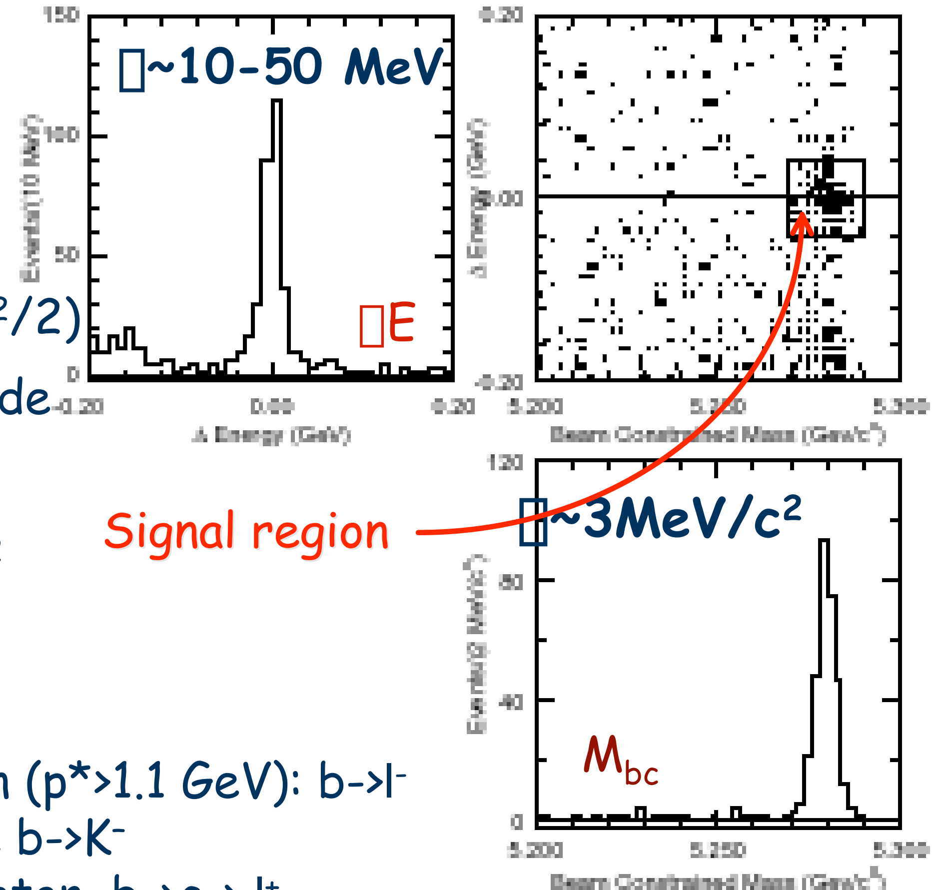
1) *CP* final state reconstruction
exploit
- exclusive pair production of B
- narrow resolution of collision energy

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

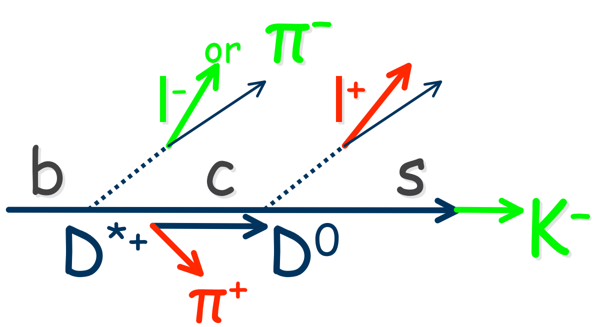
σ~10-50 MeV, depending on mode

M_{bc} (Beam-constrained mass)

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



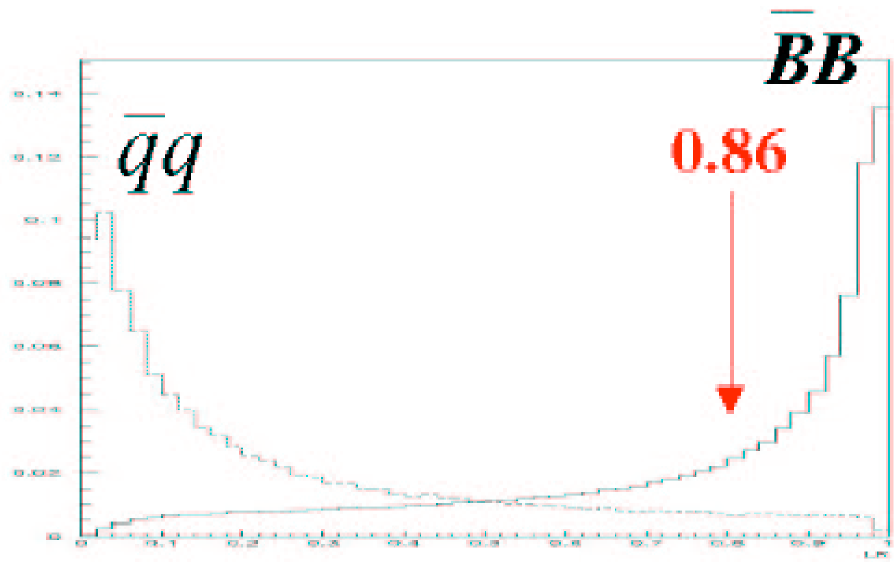
2) Flavor tagging: sign of other b
all remaining particles in the event



high-p lepton (p*>1.1 GeV): b->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

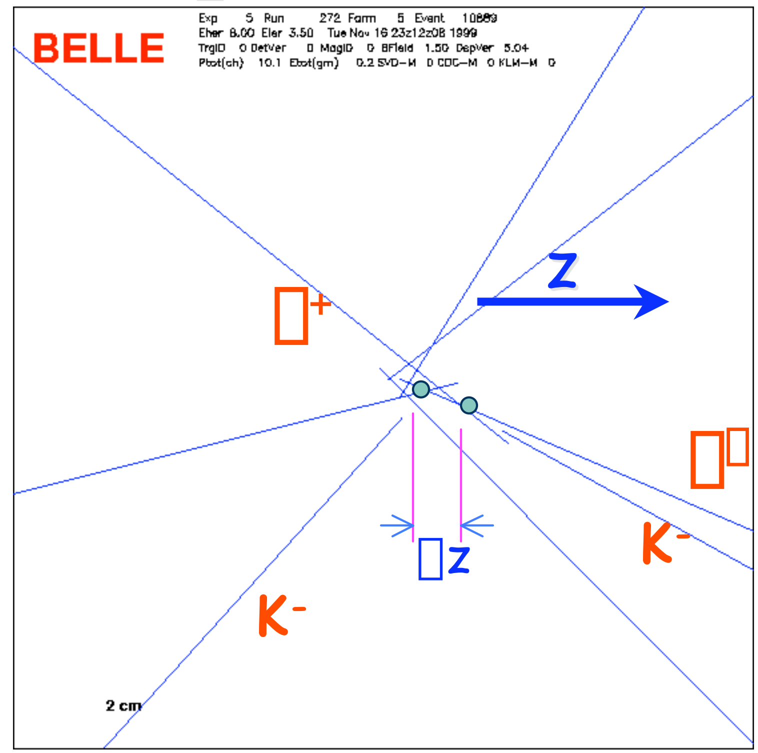
3) Continuum suppression
event parameters, likelihood ratio



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

4) Vertex reconstruction

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



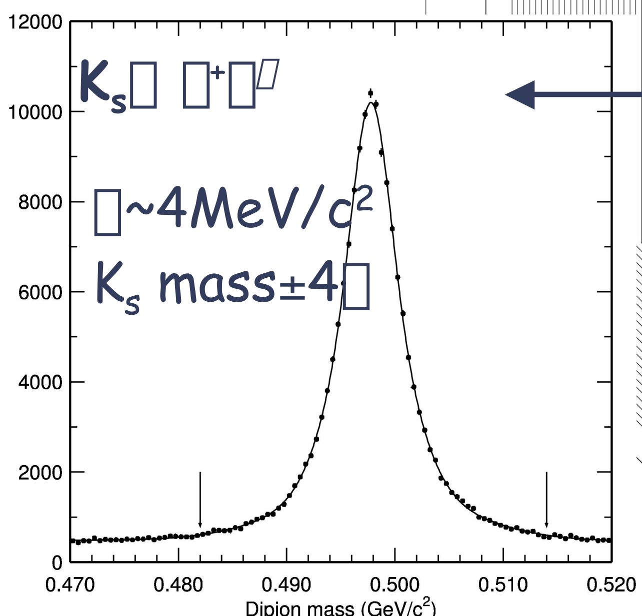
5) Fit to Δt distribution:
unbinned maximum likelihood

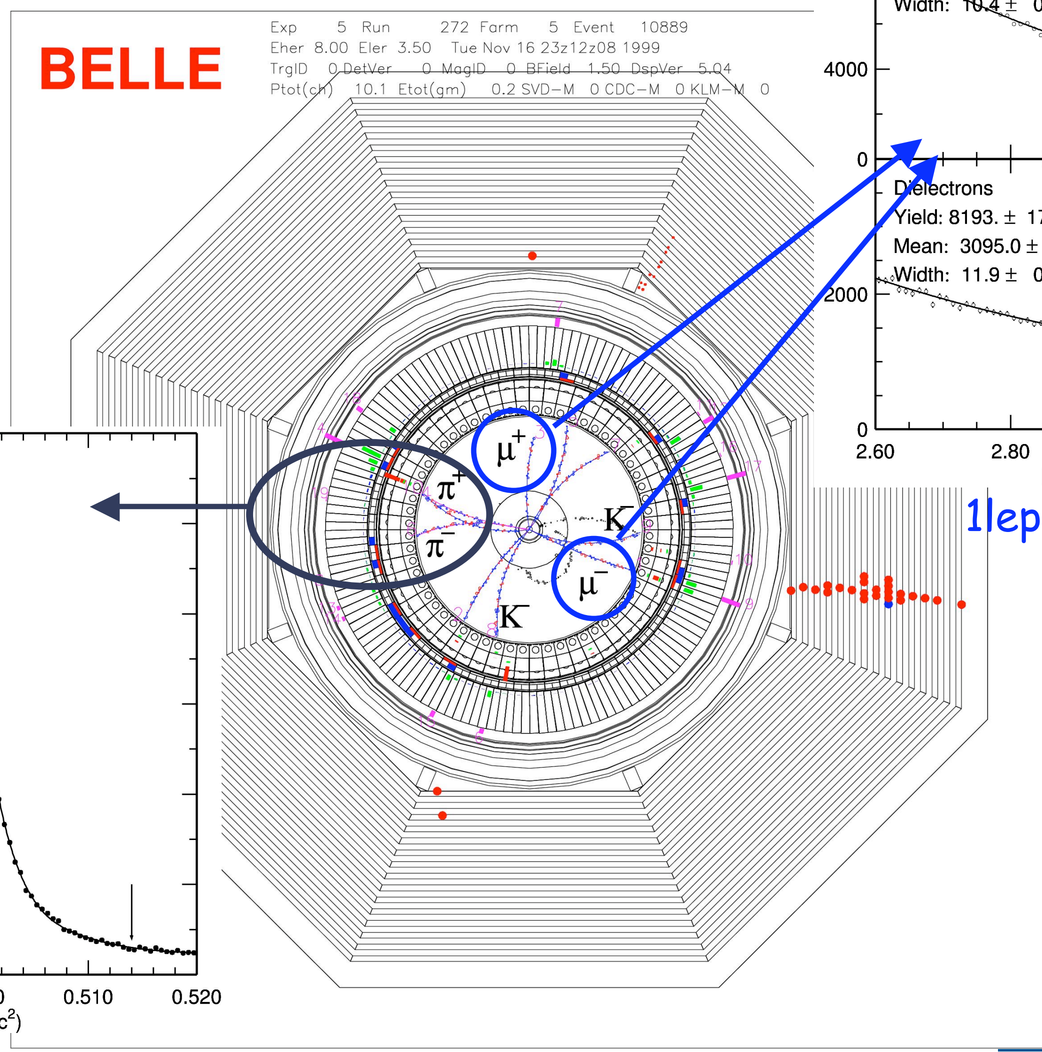
e.g., for sin2ϕ_1 - reconstruct CP eigenstate decays

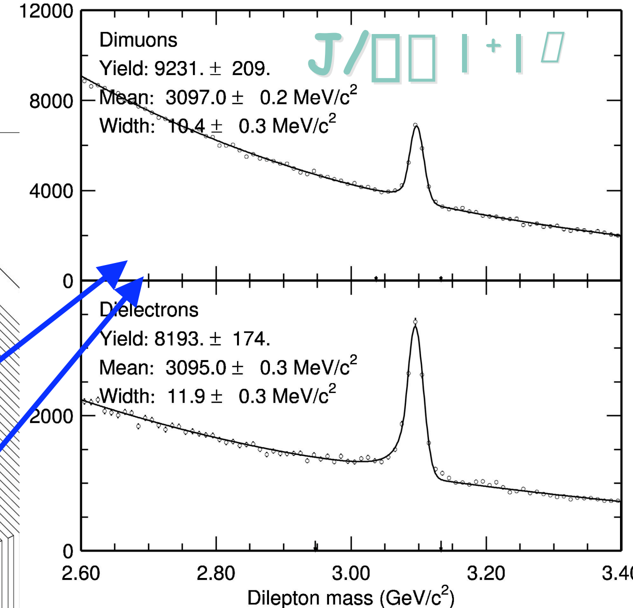
"CP-side tag"

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

"golden mode"





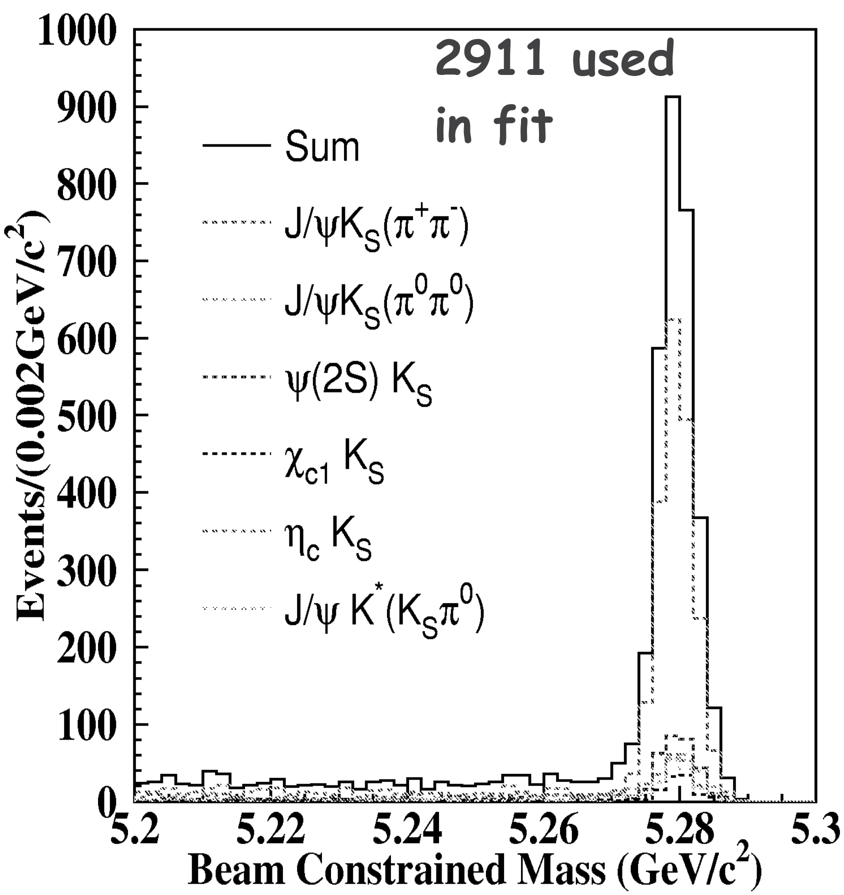


1lepton+1"not-hadron"

sin2φ1: {charmonium}+K_s tag (CP=-1)

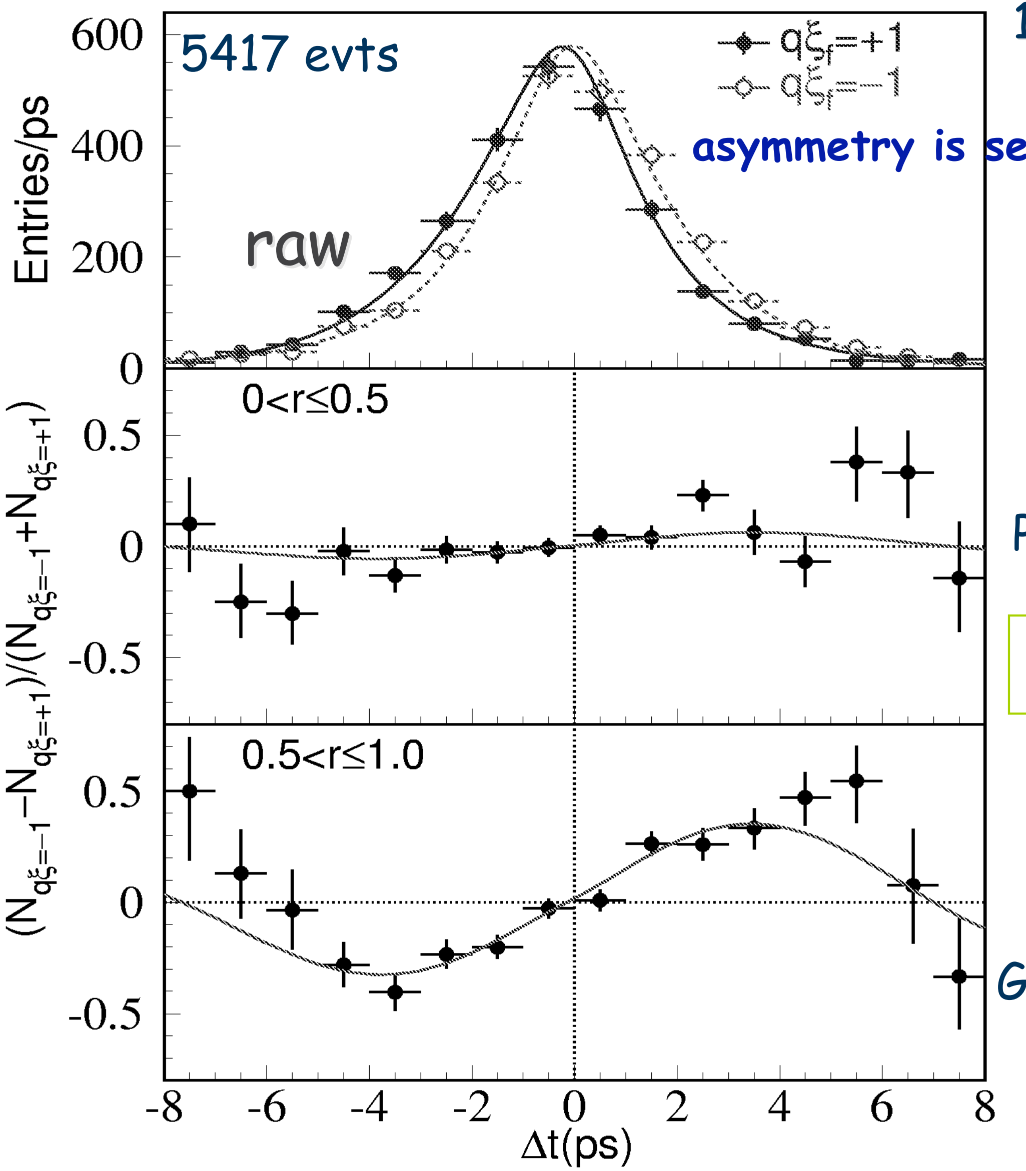
BELLE-CONF-0353

Fully reconstructed



Mode	N_{ev}	Purity
$J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	1997	0.976 ± 0.001
$J/\psi(\ell^+\ell^-)K_S^0(\pi^0\pi^0)$	288	0.82 ± 0.02
$\psi(2S)(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	145	0.93 ± 0.01
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0(\pi^+\pi^-)$	163	0.88 ± 0.01
$\chi_{c1}(J/\psi\gamma)K_S^0(\pi^+\pi^-)$	101	0.92 ± 0.01
$\eta_c(K_S^0K^-\pi^+)K_S^0(\pi^+\pi^-)$	123	0.72 ± 0.03
$\eta_c(K^+K^-\pi^0)K_S^0(\pi^+\pi^-)$	74	0.70 ± 0.04
$\eta_c(p\bar{p})K_S^0(\pi^+\pi^-)$	20	0.91 ± 0.02
All with $\xi_f = -1$	2911	0.933 ± 0.002
$J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$	174	0.93 ± 0.01

Measurement of $\sin 2\phi_1$



140 fb^{-1}

asymmetry is seen in raw data

Poor tags

$\sin 2\phi_1 = 0.733 \pm 0.057 \pm 0.028$

consistent with no direct CP violation

Good tags

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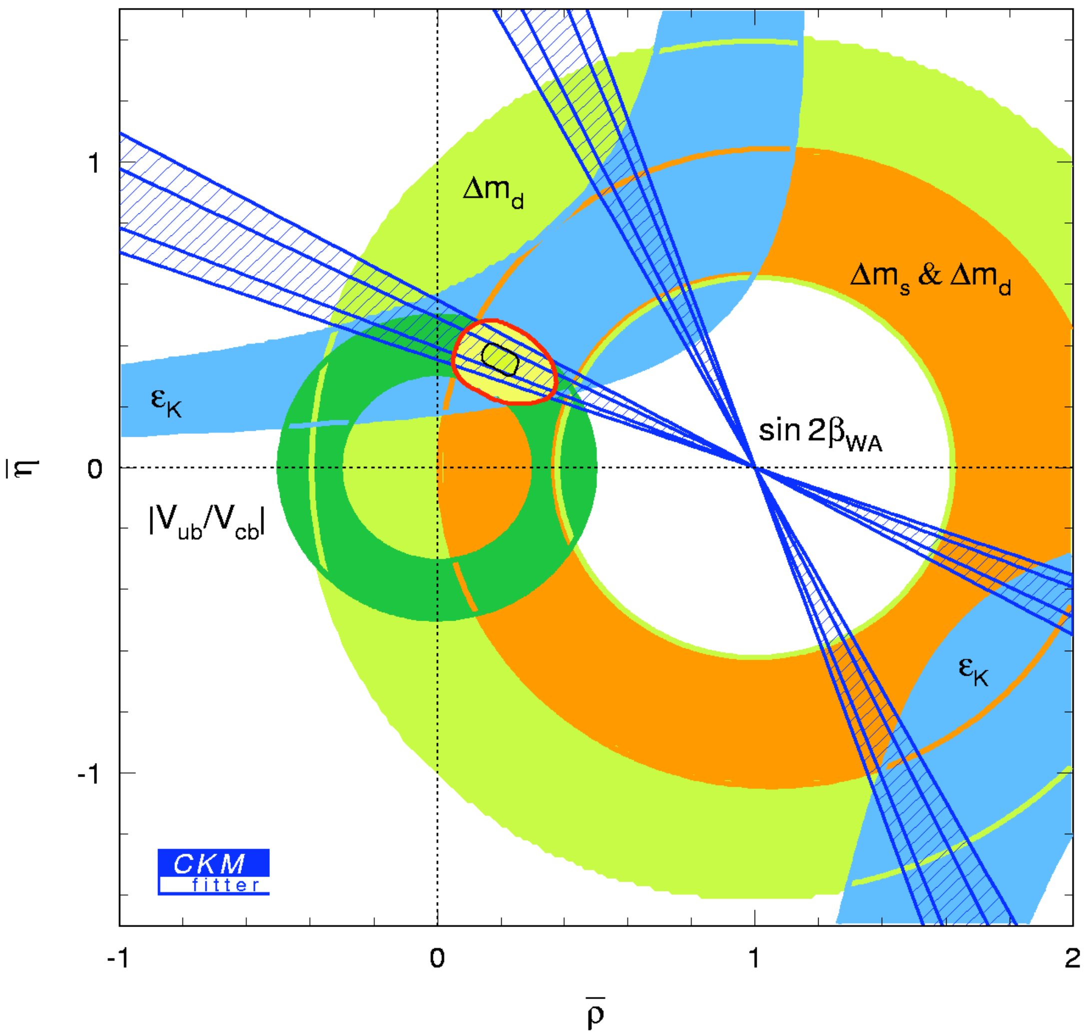
world average from {cc}K



sin2□$_1$ (Belle 2003, 140 fb^{-1})
=0.733±0.057±0.028

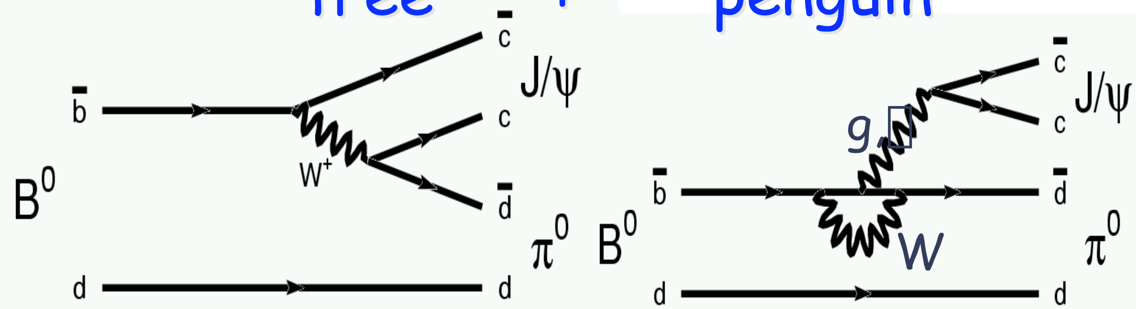
sin2□$_1$ (BaBar 2002, 81 fb^{-1})
=0.741±0.067±0.033

sin2□$_1$ (World Av.)

=0.736±0.049

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

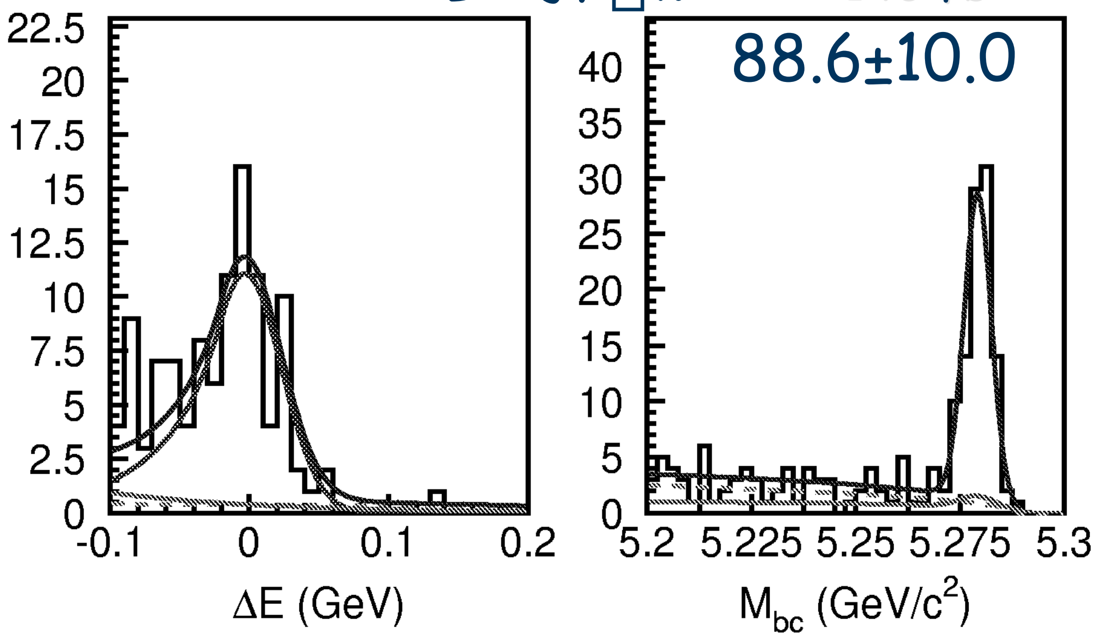
tree + penguin

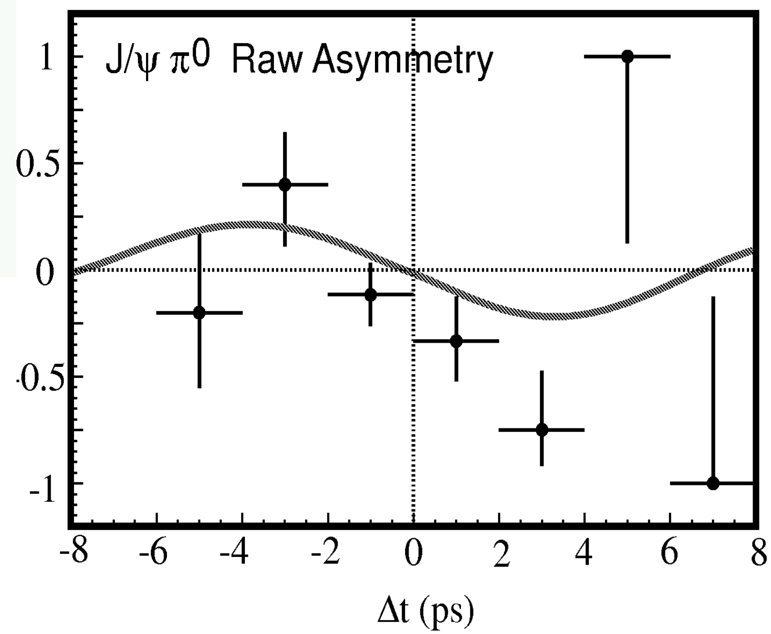


(relative amplitudes, strong phase not known)

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

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





$S = -0.72 \pm 0.42 \pm 0.08$

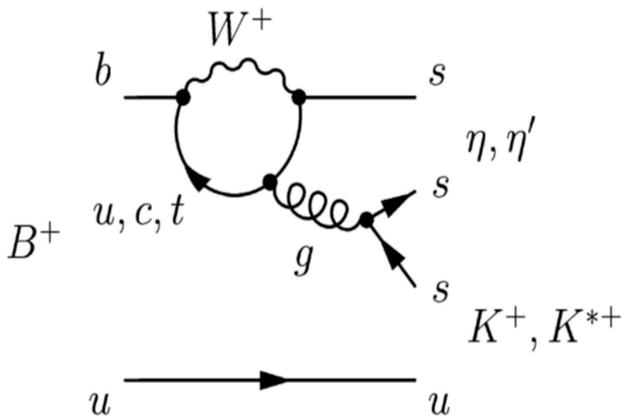
$A = -0.01 \pm 0.29 \pm 0.07$

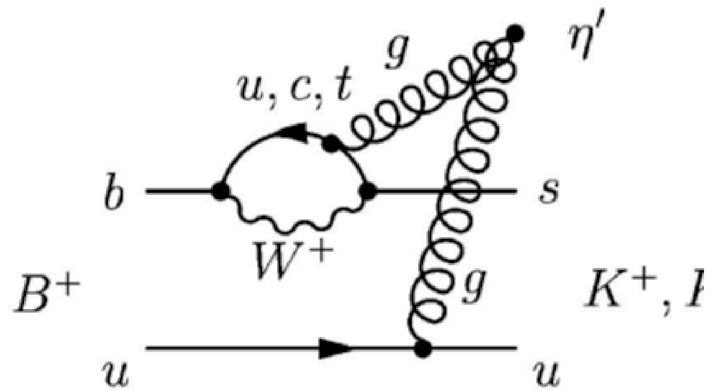
$\sin 2\phi_1$ (World Av.)=0.736 ± 0.049

BELLE-CONF-0342+

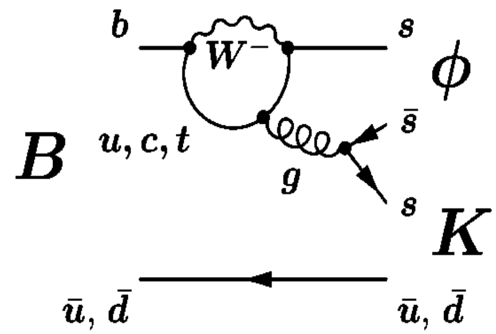
More time-dependent $\sin2\phi_1$ – or new physics?

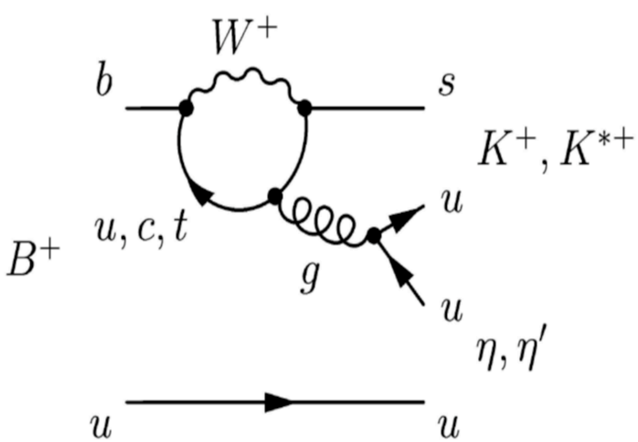
modes dominated by b->s$q\bar{q}$ penguins

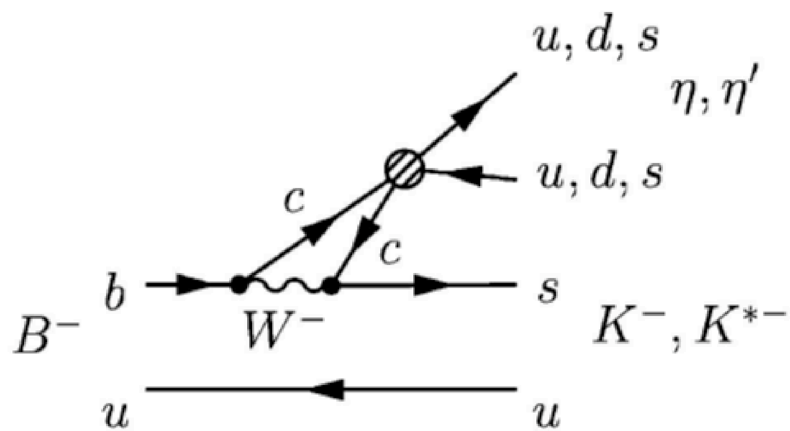




Theoretically cleanest



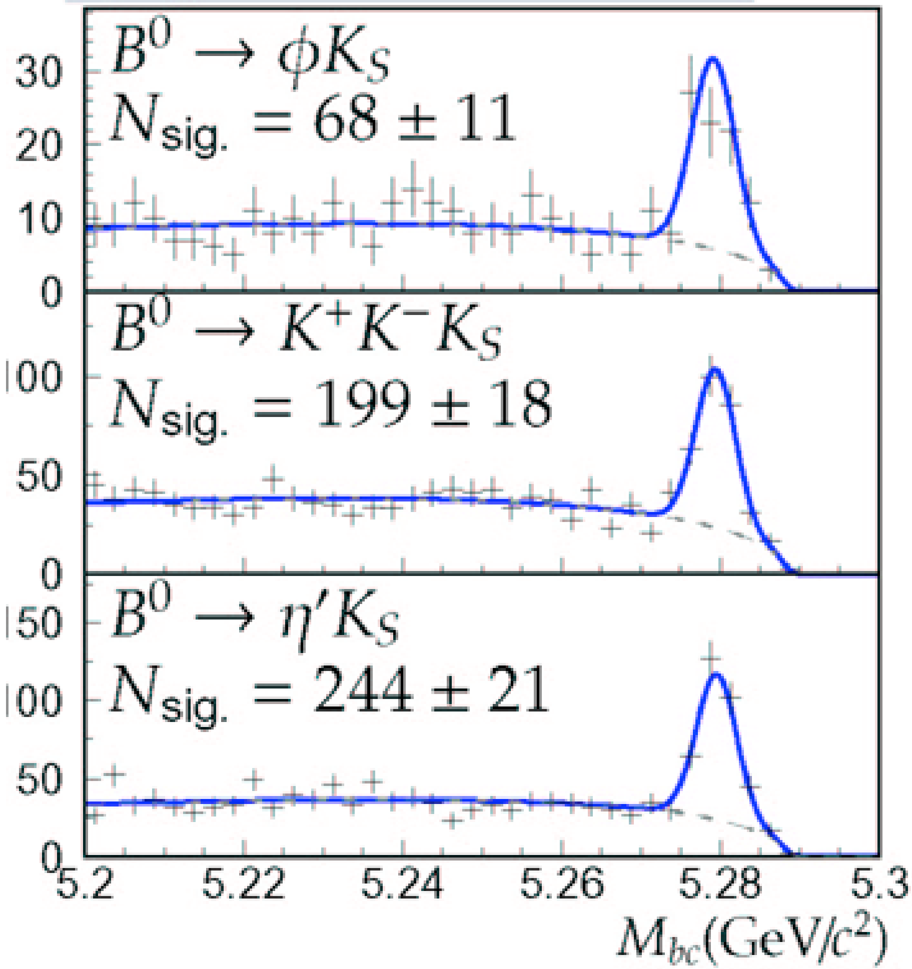




in the absence of New Physics, S = $\sin2\phi_1$

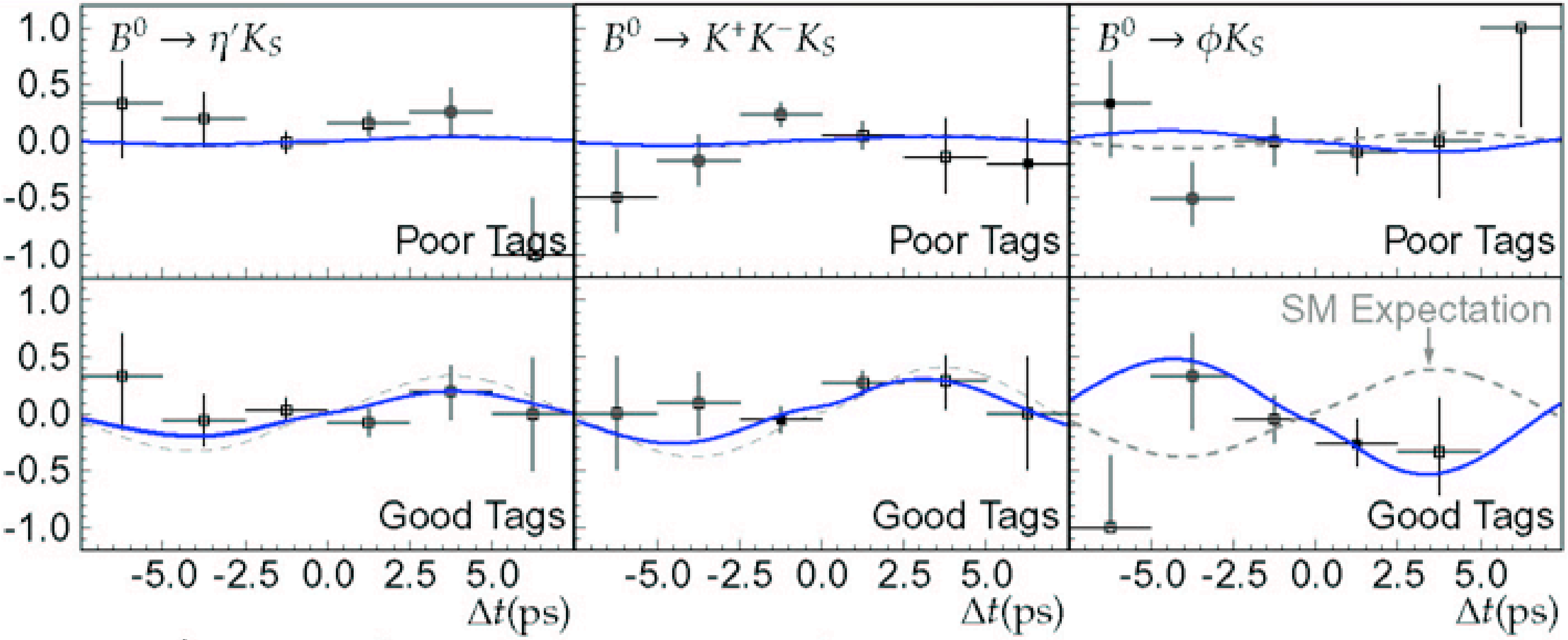
Reconstruction of b->sqq

Mode	N_{ev}	Purity
ϕK_S	106	0.64 ± 0.10
$K^+K^-K_S$	361	0.55 ± 0.05
$\eta' K_S$	421	0.58 ± 0.05



140 fb^{-1}

Time-dependence:



	$\eta' K_S$	$K^+K^-K_S$	ϕK_S
S	$+0.43 \pm 0.27 \pm 0.05$	$+0.51 \pm 0.26 \pm 0.05^{+0.18}_{-0.00}$	$-0.96 \pm 0.50^{+0.09}_{-0.11}$
A	$-0.01 \pm 0.16 \pm 0.04$	$-0.17 \pm 0.16 \pm 0.04$	$-0.15 \pm 0.29 \pm 0.07$

uncertainty in CP content.

[sin2ϕ_1(world avg) = 0.736±0.049] differs by 3.5σ PRL 91, 261602 (2003)

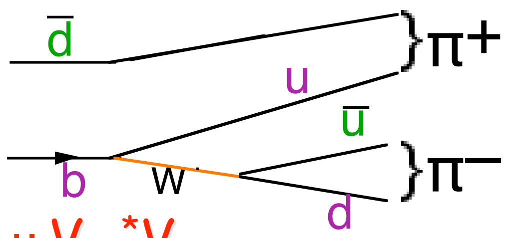
... however {Babar: +0.45±0.43±0.07}

sin2ϕ_2: $B^0 \to \pi^+\pi^-$

ϕ_2 =arg $\frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}$

2 paths, each w/wo mixing:

Tree (T)

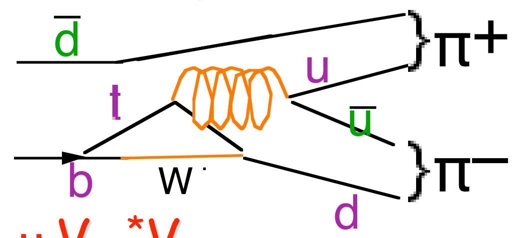


µ $V_{ub}^*V_{ud}$

mixing+ "

µ $V_{tb}^{*2}V_{td}^2V_{ub}V_{ud}^*$

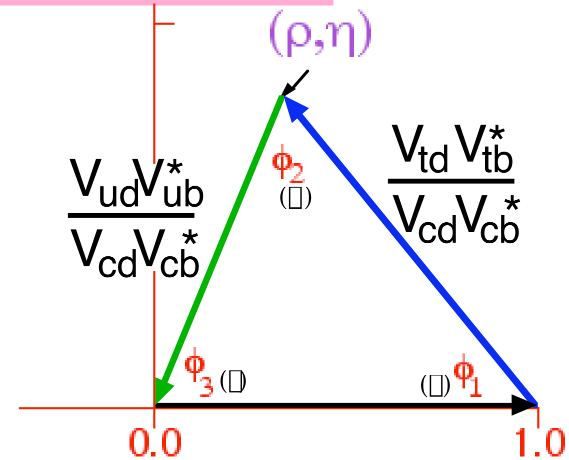
Penguin



µ $V_{tb}^*V_{td}$

mixing+ "

µ $V_{tb}^{*2}V_{td}^2V_{tb}V_{td}^*$



Bottom line: A_{CP} may include direct CP violation

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

- if T dominates, $A_{\pi\pi}=0$, $S_{\pi\pi}=\sin 2\phi_2$
- if P, T comparable, $A_{\pi\pi}\neq 0$, $S_{\pi\pi} \sim \sin(2\phi_2+2□)\cdot 2/(|□|^2+1)$

difference of strong phase

≠1 if direct CP violation

$B^0 \to \pi^+\pi^-$ reconstruction issues

… less clean than $B^0 \to J/\psi K_s$:

- "physics bkg" $B^0 \to K^+\pi^-$ => hadron ID, kinematics
  dE/dx, TOF, Aerogel – "positive ID" ϵ_π=91%, ϵ_K=10%
- continuum => event shape {qq "jet-like" vs BB "spherical")
  Fisher discriminant from modified Fox-Wolfram moments
  B candidate direction relative to beam axis
  Construct Likelihood ratio $LR=L_{BB}/[L_{BB}+L_{qq}]$, 2 selections:
  - $LR > 0.86$ {ϵ_{BB}=53%, ϵ_{qq}=5%}
  - $0.86 > LR > LR_{min}$ (cut depends on flavor tag classification)

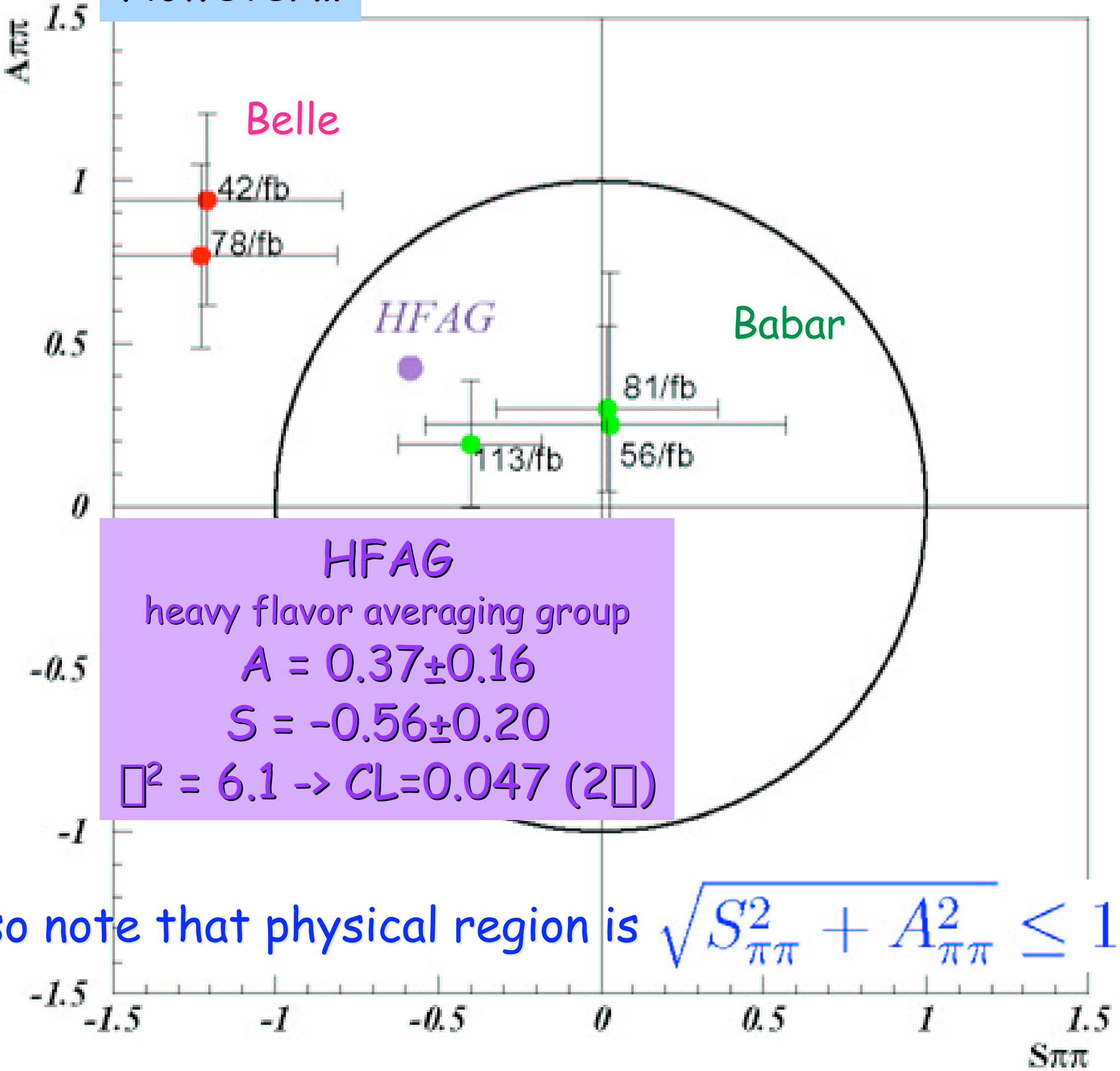
history

Belle results

"Study of CP-Violating Asymmetries in $B^0 \to \pi^+\pi^-$ Decays"
{PRL 89, 071801 (2002)}
(42 fb^{-1} ~45M B pairs)

"Evidence for CP-Violating Asymmetries in $B^0 \to \pi^+\pi^-$ Decays …"
{PRD 68, 012001 (2003)}
(78 fb^{-1} ~85M B pairs)

However…



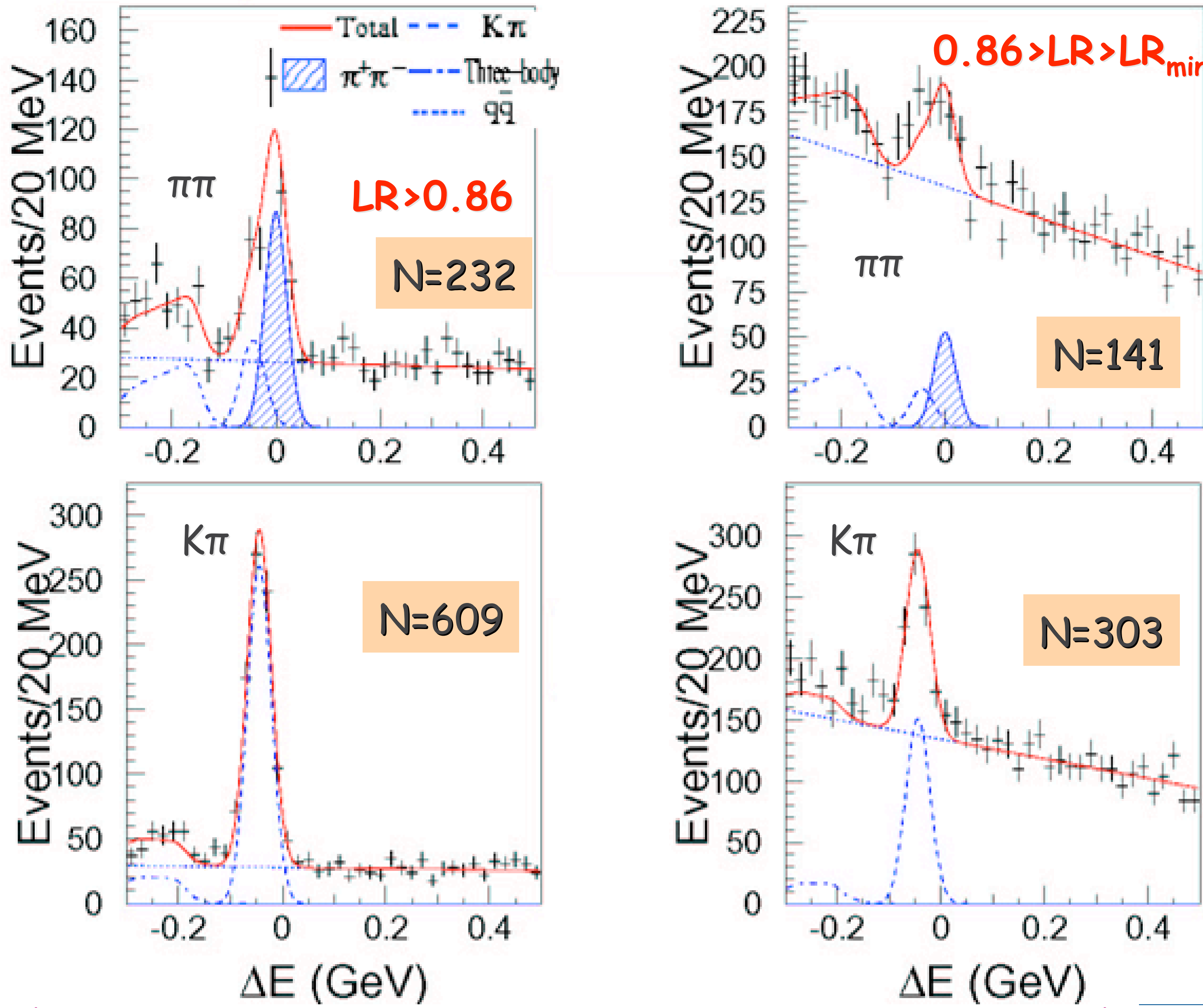
HFAG
heavy flavor averaging group
A = 0.37±0.16
S = -0.56±0.20
χ^2 = 6.1 -> CL=0.047 (2σ)

… also note that physical region is $\sqrt{S_{\pi\pi}^2 + A_{\pi\pi}^2} \leq 1$

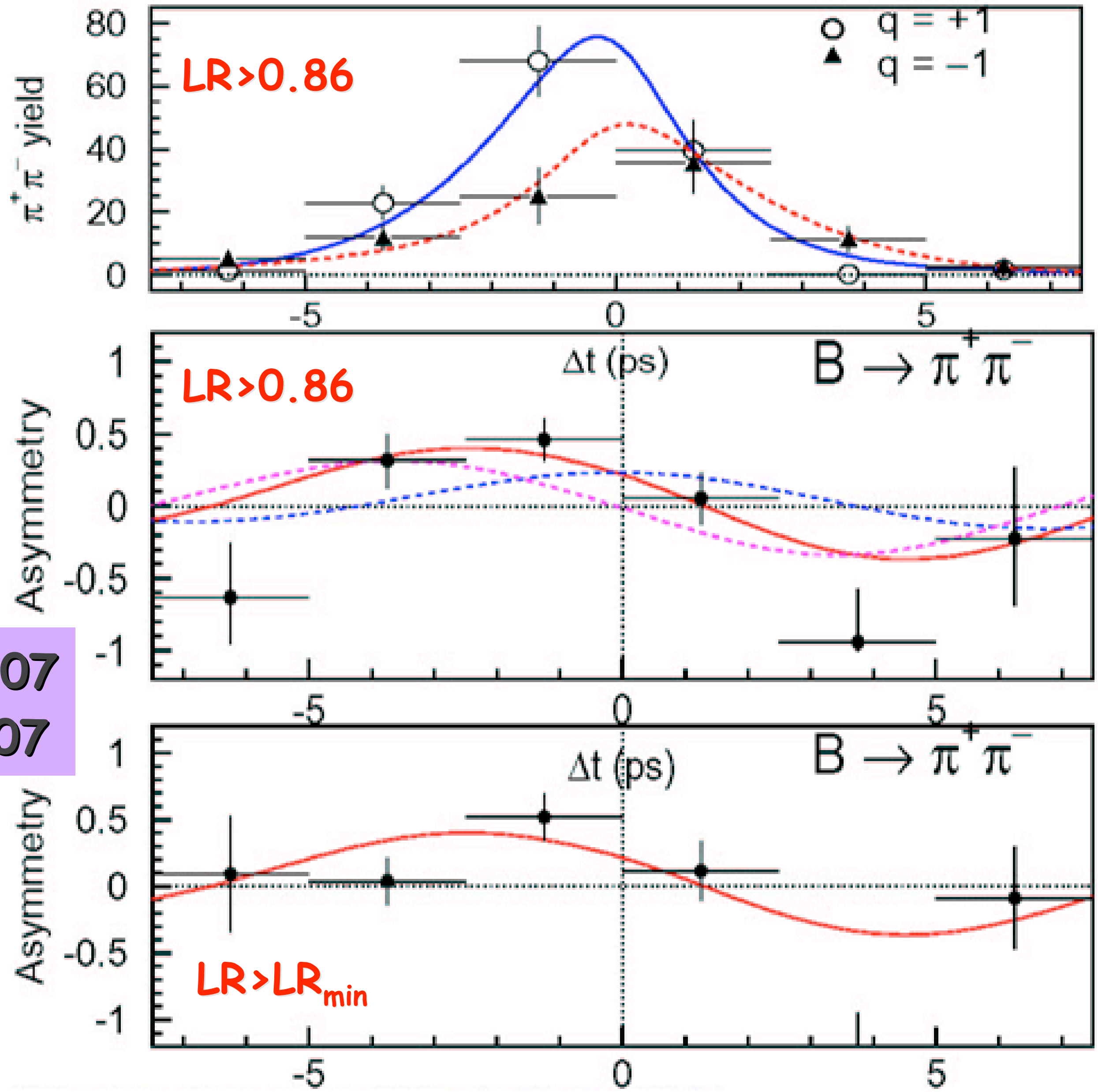
news

- additional data 78 fb^{-1} -> 140 fb^{-1}
- signal fraction 1d -> 2d (ΔE, M_{bc}) fit: improved robustness
- improved continuum suppression
- new independent analysis: binned maximum likelihood in Δt
  different resolution functions, blind

$B^0 \to \pi^+\pi^-$ and $K^+\pi^-$ final samples



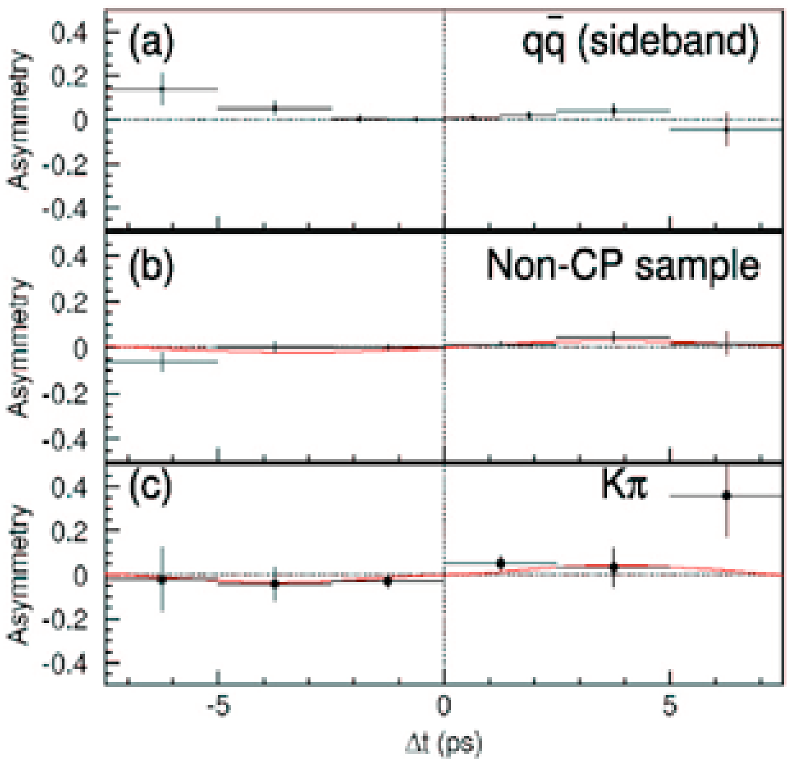
Result of fit



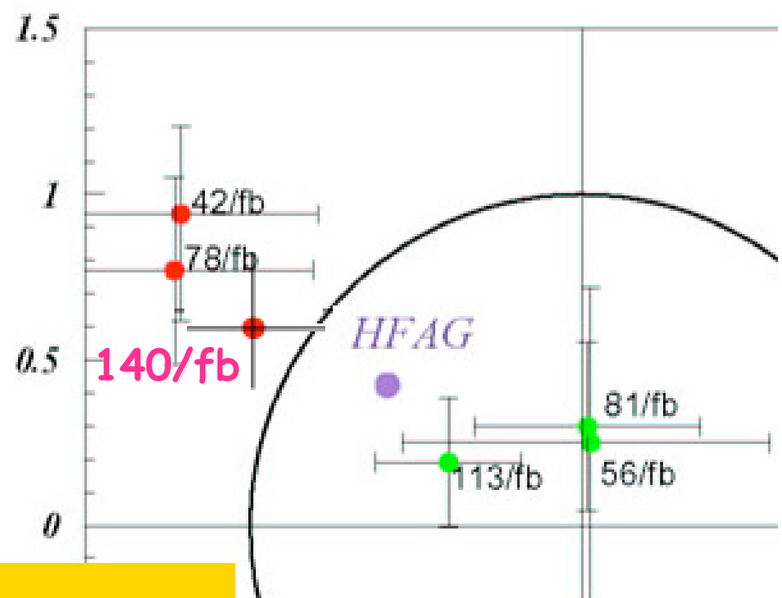
A = +0.58±0.15±0.07
S = −1.00±0.21±0.07

Validation of result

- no CP asymmetry observed where none expected



- many subsamples – consistent results
- independent selection with binned fit gives ~same result
- ensemble simulation study – confidence of unphysical result is reasonable



"Observation of Large CP Violation and Evidence for Direct CP Violation in $B^0 \to \pi^+\pi^-$ Decays," submitted to PRL

Conclusion

Observation of CP violation (5.2σ)

Evidence for direct CP violation (3.2σ)

Summary

Belle in 2004:

- KEKB *luminosity* $1.20\times10^{34}cm^{-2}s^{-1}$ (design: 1×10^{34}); >220M B pairs
- $\sin2\phi_1$ is now a "precision" measurement
- first results on alternative probes of $\sin2\phi_1$ (or new physics!)
  - $B\to J/\psi\,\pi^0$ - penguin may be small (need more data)
  - surprise deviation in $B\to\phi K_s$ - 3.5σ - hints of new physics?
  - consistency with SM in other b->sss
- developing sensitivity to ϕ_2, ϕ_3
  - $B\to\pi^+\pi^-$ - first evidence of direct CP violation?
- observations/hints in many modes, possibly CP in future

Next

- 500 fb^{-1} by 2005
- Luminosity > design
- the CP challenge: heating up - stay tuned!