KEK, August 13, 2003

CP Asymmetries: New Results from Belle

- Weak interaction: CP, CKM matrix
- B(eauty) mesons & CP asymmetry
- B production: $e^+e^- \to$ (4S) at KEKB
- Belle experiment
    - Highlights for 2003
    - Selected CP & other results (preliminary)
- Plans

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CP Violation

Why is it of interest?

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

Weak interaction - the only known force that

- violates CP symmetry (a little)
  .. but to 1998, only in K_L (1963)
- violates P symmetry (maximally)

… but preserves CP symmetry (mostly)

right-handed particles, left-handed antiparticles.

no coupling to LH particles, RH antiparticles.

- allows particle to change identity (flavor)

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

… step back, look at weak coupling strengths…

Weak coupling strengths

Standard Model = 12 fermion flavors (+antifermion)

+ strong, EM, weak forces,
unification of EM+weak

3* generationsx2 typesx2 ea,
stable, but for weak interaction

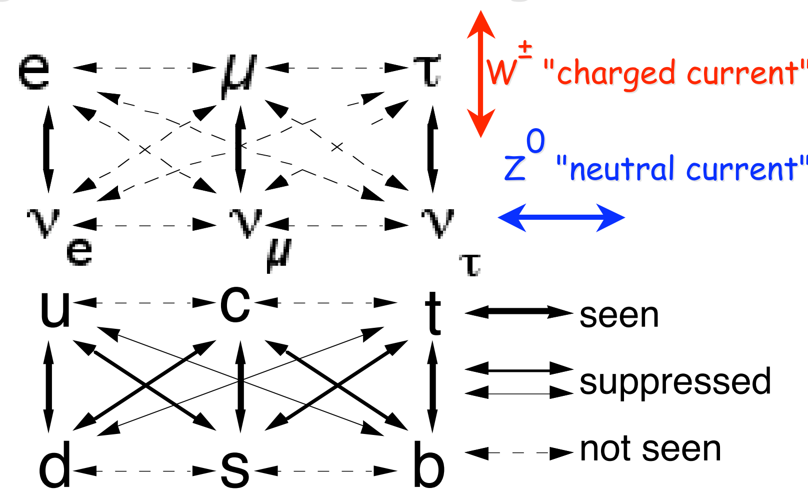
*generations distinguished only by mass

Couplings:

- no generation x-ing, except charged-current quark
- leptons: ~same

quarks: all different, approx generation-conserving

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



Inelegant!!

Elegance restored: GIM mechanism

Picture

- strong doublets, generations "degenerate," perturbed by weak force:

  new doublets $\begin{matrix} u \\ d' \end{matrix}$ $\begin{matrix} c \\ s' \end{matrix}$ $\begin{matrix} t \\ b' \end{matrix}$

  no generation x-ing, universal W-coupling (=g_F, seen in leptons)

  d', s', b' are linear combinations of d, s, b:

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

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

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

unitarity →

↑

$V_{ji}{}^* V_{jk} = □_{ik}$

explicit parametrization(Wolfenstein):

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

from decay rates,

□ = 0.220 ± 0.002

A = 0.81 ± 0.08

|□□i□| = 0.36 ± 0.09

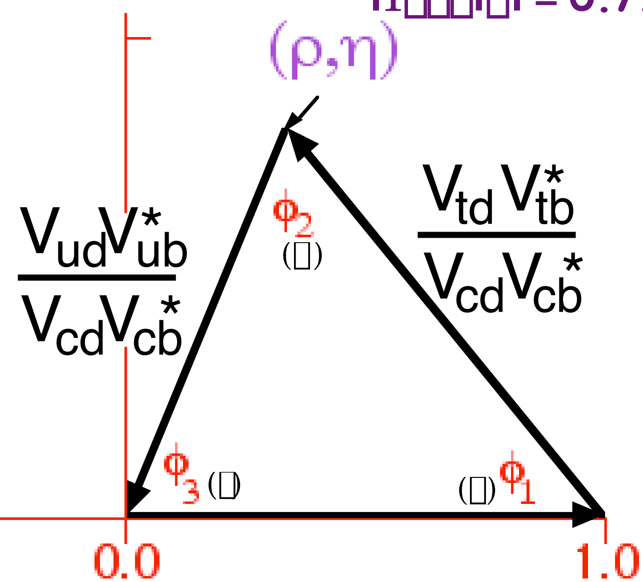
|1□□□i□| = 0.79 ± 0.19

{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 - due to ≥3 generations

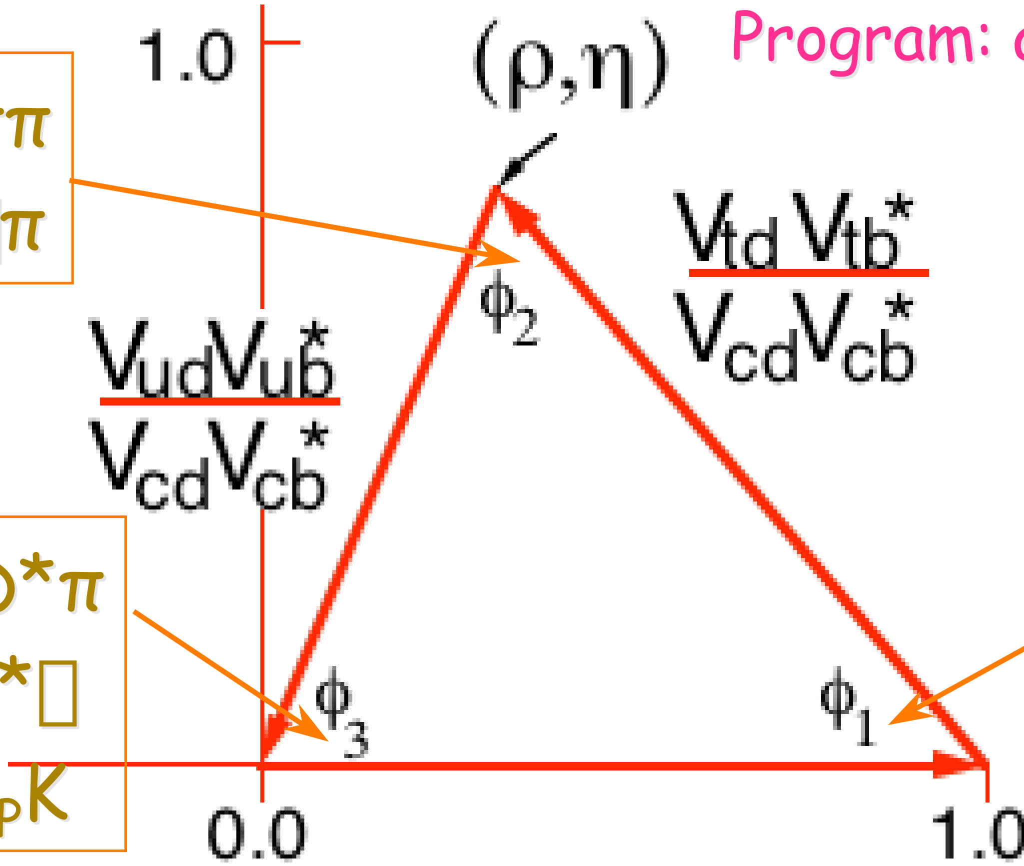
-> need process w. all 3 (occurs with many B decays), interference in ≥2 processes (but not too many)

-> probe different angles w different decays

Program: are all asymmetries consistent w single KM phase?

B^0->ππ

B^0->□π



first result

B^0->J/□K_s

B^0->□K_s

B^0->$D^{(*)}$ $D^{(*)}$

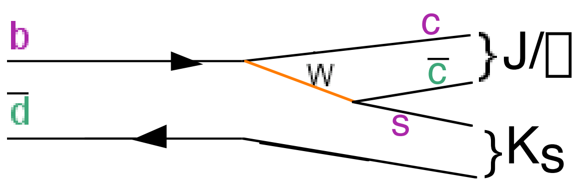
B^0-> $D^*\pi$

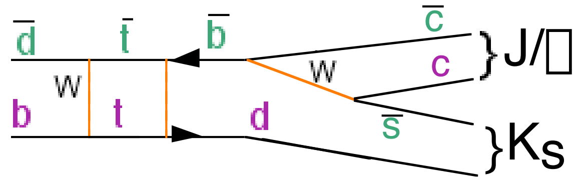
B^0->D^*□

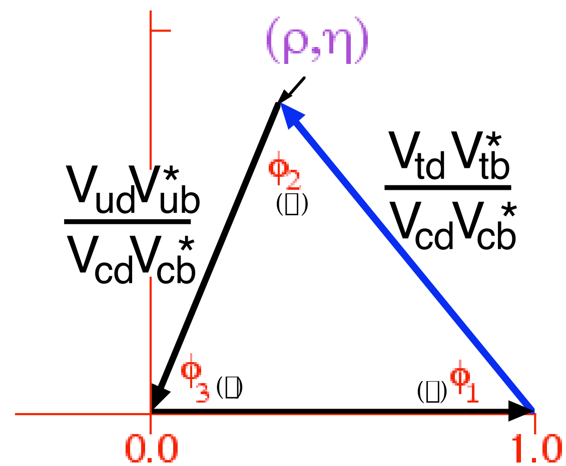
B->D_{CP}K

e.g. B -> J/ψ K_s for sin $2\phi_1$ (Sanda/Bigi/Carter)

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







(no cc of hadronic phase under CP)

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

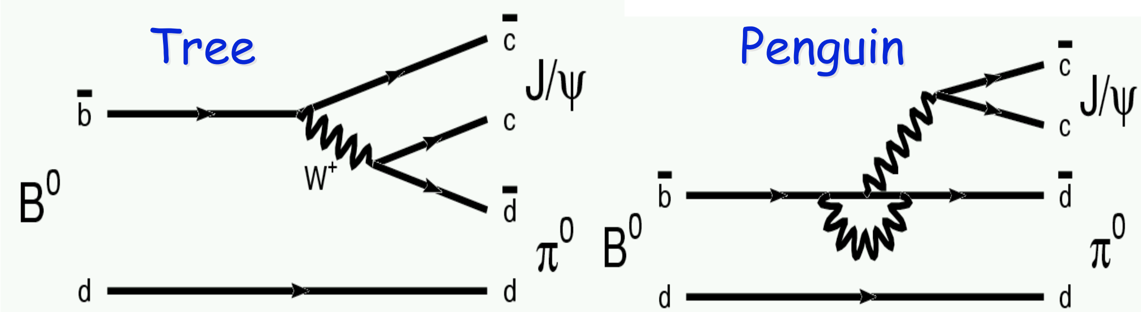
$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b\eta_{CP}\sin 2\phi_1 \sin(\Delta m \Delta t));$$

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

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

CP phenomenology: variations

e.g. B -> J/□π^0 2 paths, different phases, + mixing

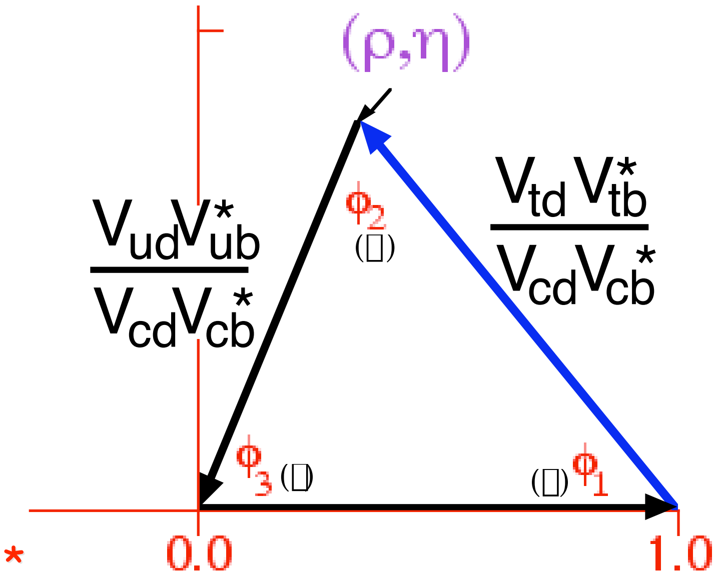


□$V_{cb}^*V_{cd}$ □$V_{tb}^*V_{td}$

(relative amplitudes, strong phase not known)

mixing+ " mixing+ "

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



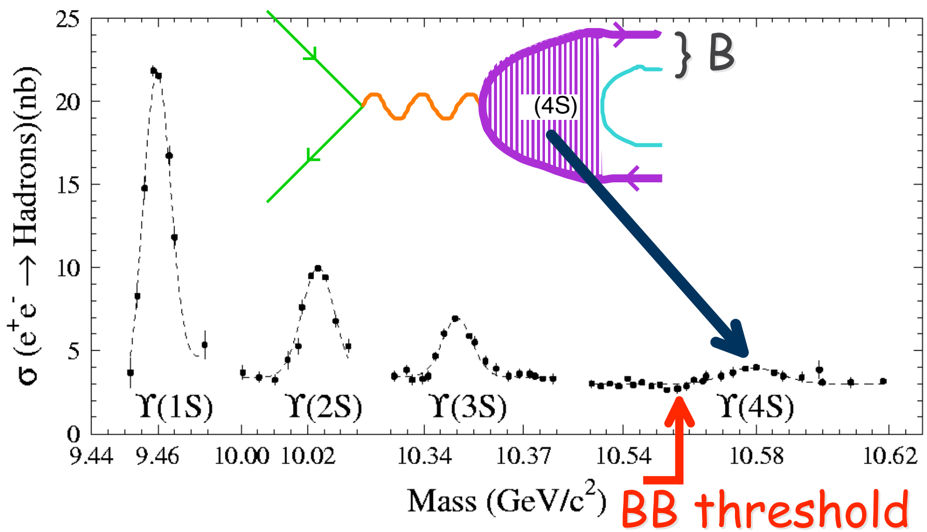
$$q = \begin{pmatrix} +1 \text{if } B_{t=0} = B^0 \\ -1 \text{if } B_{t=0} = \bar{B}^0 \end{pmatrix}$$

Bottom line: "direct" CP asymmetry possible

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

"direct" asym

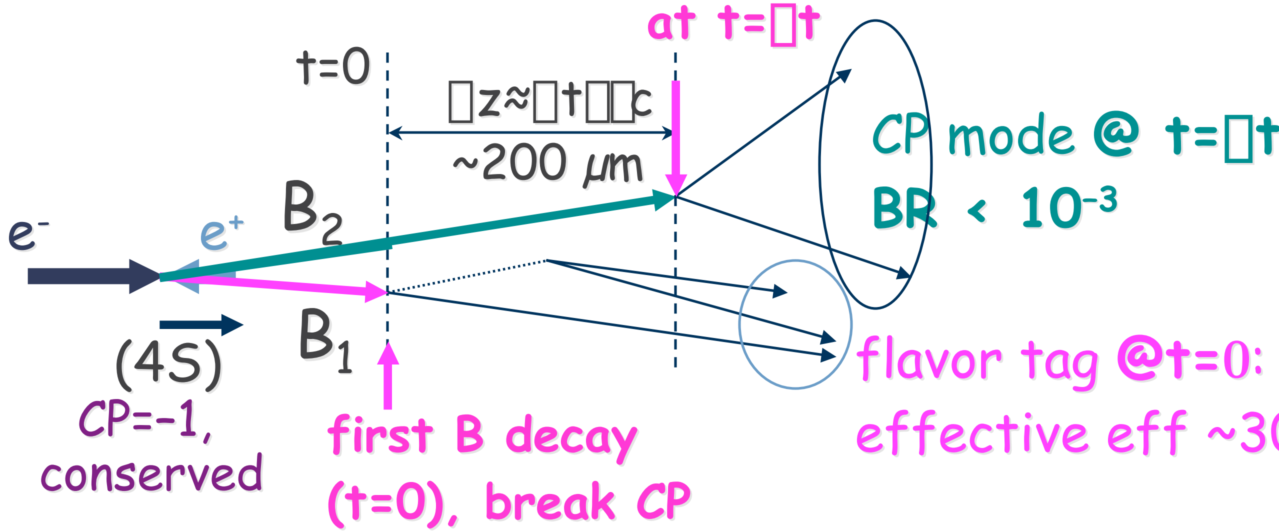
B production: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



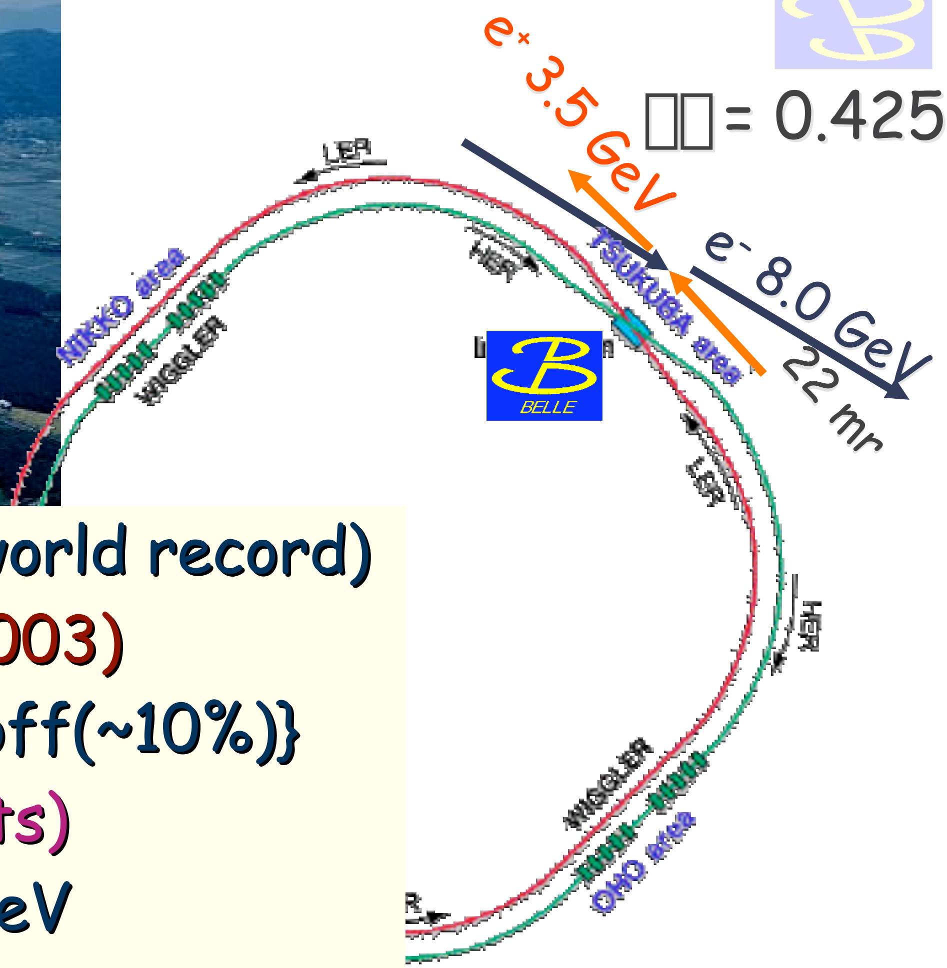
Δt by asymmetric e^+e^- -> ϒ(4S)

What else is needed?

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



KEKB



L_{max} = 1.06 X 10^{34} $cm^{-2}s^{-1}$ (world record)

Data (6/1999-6/2003)

$\int L dt$ = 158 fb^{-1}@{ Υ(4S)+off(~10%)}

(1.52x10^8 B events)

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

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

Belle detector

Charged tracking/vertexing

- SVD: 3-layer DSSD Si μstrip
- CDC: 50 layers (He-ethane)

Hadron identification

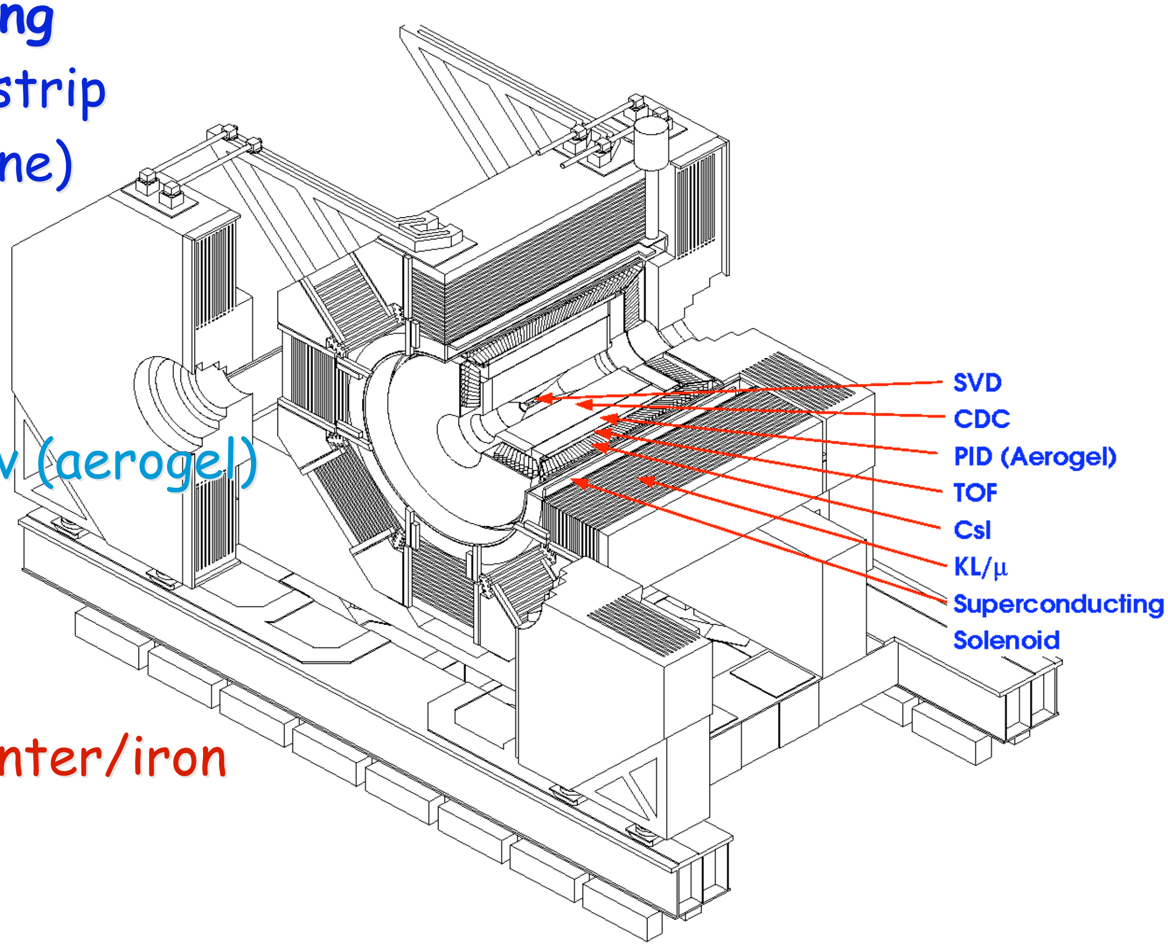
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon

- ECL: CsI calorimeter

Muon/KL

- KLM: Resistive plate counter/iron



...the people

VOLUME 86, NUMBER 12 PHYSICAL REVIEW LETTERS 19 MARCH 2001

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

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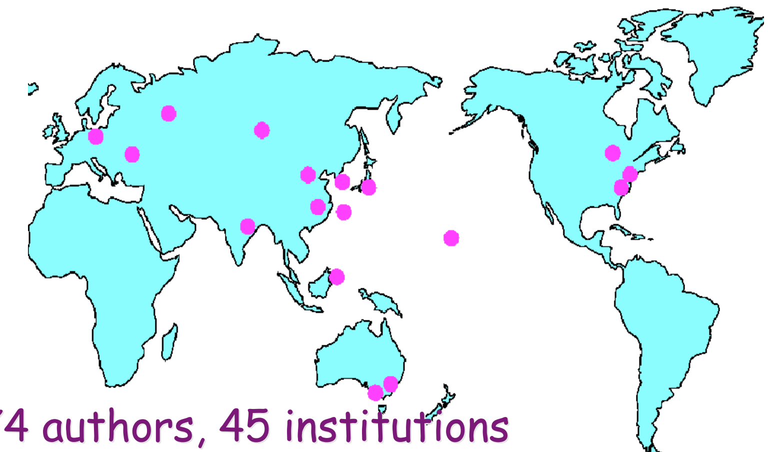

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(Received 9 February 2001)

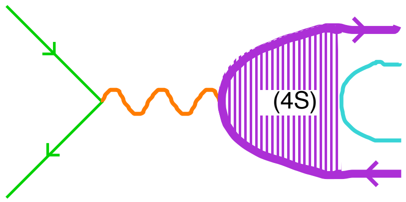
We present a measurement of the standard model *CP* violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a 10.5 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. One neutral B meson is reconstructed in the $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, 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 $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$.

DOI: 10.1103/PhysRevLett.86.2509 PACS numbers: 11.30.Er, 12.15.Hh, 13.25.Hw

Belle physics results

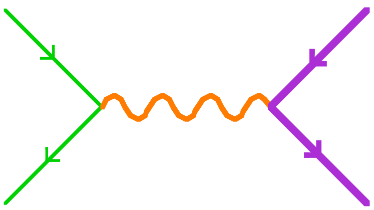
58 papers published or in press (1st in 3/2001)

54 abstracts submitted to XXI Lepton-Photon (Fermilab)

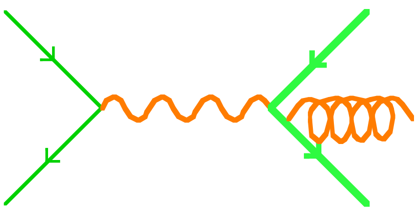


18 - CP asymmetry in B decay

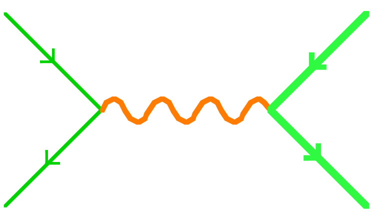
25 - B decay non-CP



8 - charm hadrons



1 - QCD



2 - tau

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

Recent highlights

CP and related

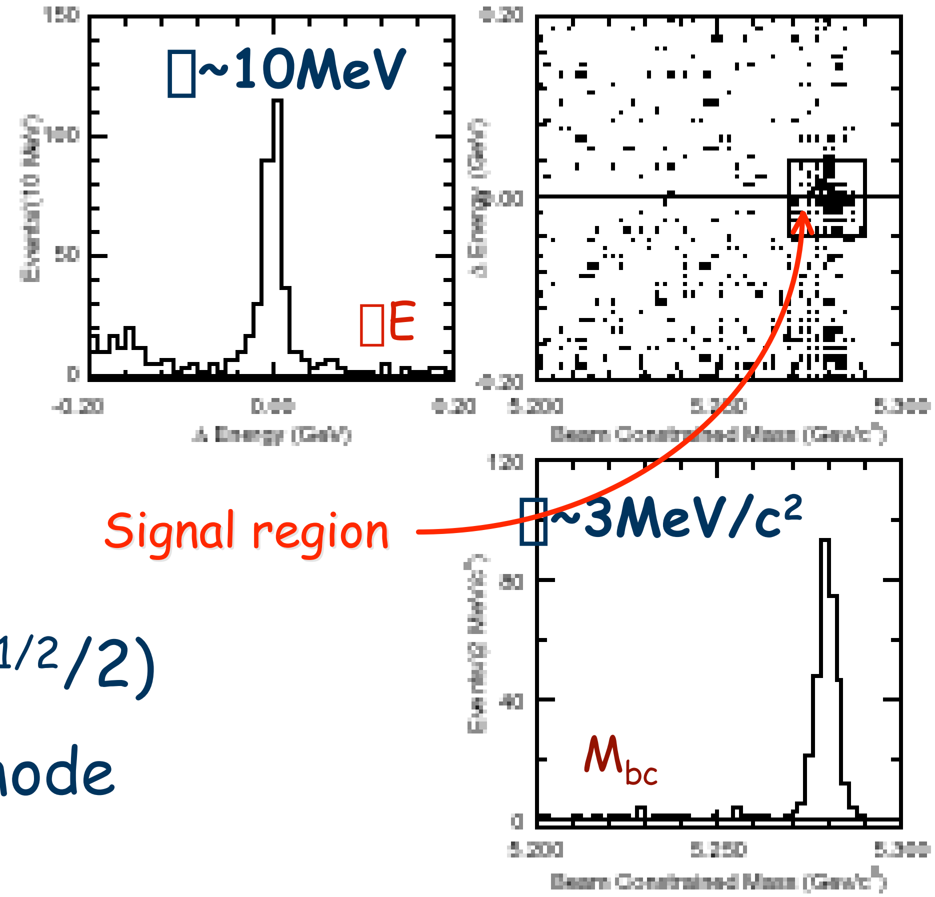
- time-dependent CP measurements
  - update of $J/□ K_s$ ($□_1$)
  - with $J/□\pi^0$($\sim□_1$), $D^{*+}\pi^-$($2□_1+□_3$), $□K_s$($□_1$)
- evidence/observation
  - B-> $K^*l^+l^-$, $\pi^0\pi^0$, D^+D^-, $\pi^0□^0$
- new method for $□_3$: Dalitz plot analysis
  - D^0K^+ {D^0->$K_s\pi^+\pi^-$}

Charm

- new processes/ particles
  - new excited D_s states
  - new charmonium
  - first radiative: D^0->□□
- difference of CP lifetimes in D (y_{CP})

B decay reconstruction at $\Upsilon(4S)$

~3% background



Kinematics for final selection:

exploit

- exclusive pair production of B
- narrow resolution of collision energy

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

$\sigma \sim 10\text{-}50$ MeV, depending on mode

M_{bc} (Beam-constrained mass)

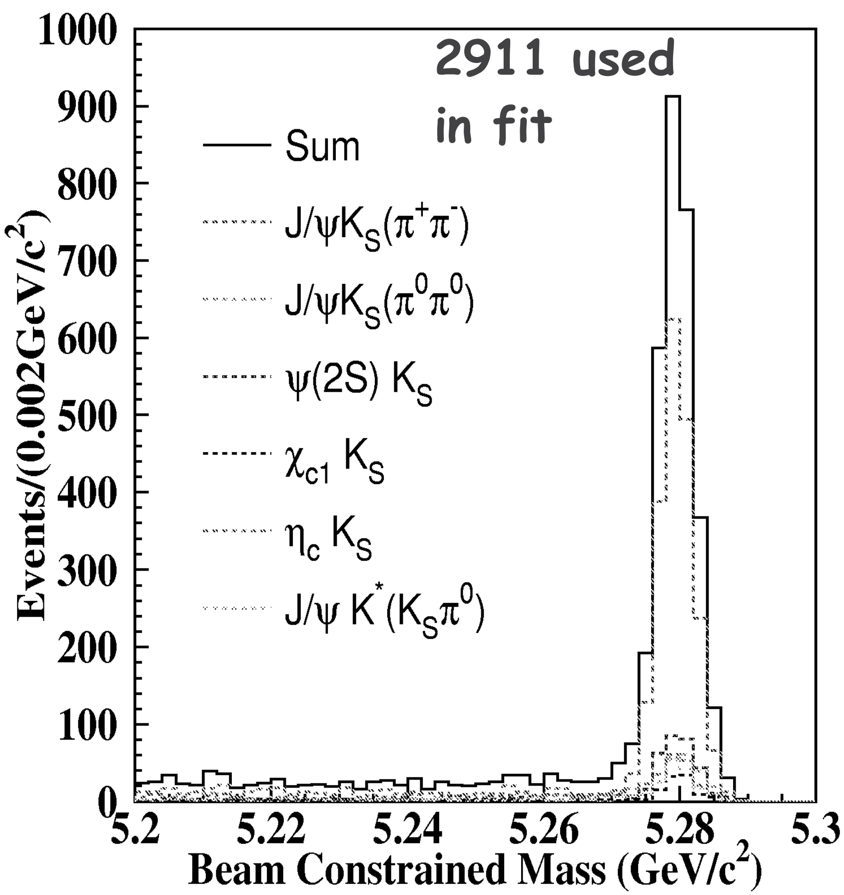
$M_{bc} = (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$

Time dependent measurements:

$\sin 2\phi_1$: {charmonium}+K_s tag (CP=−1)

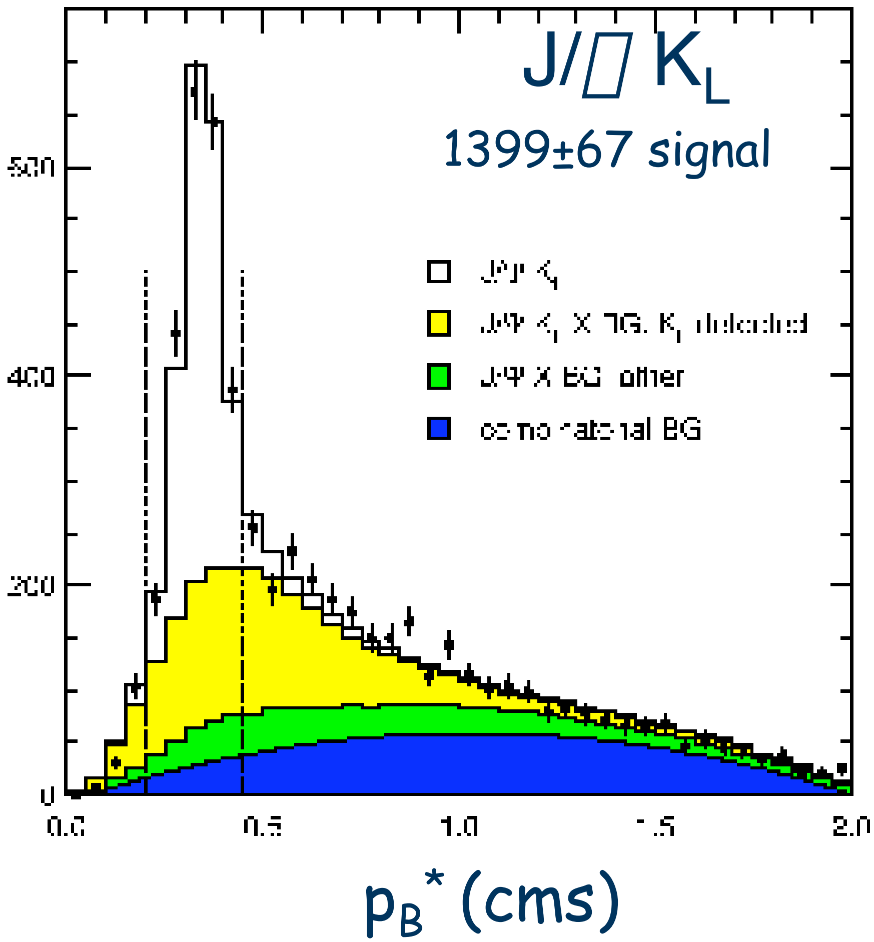
BELLE-CONF-0353

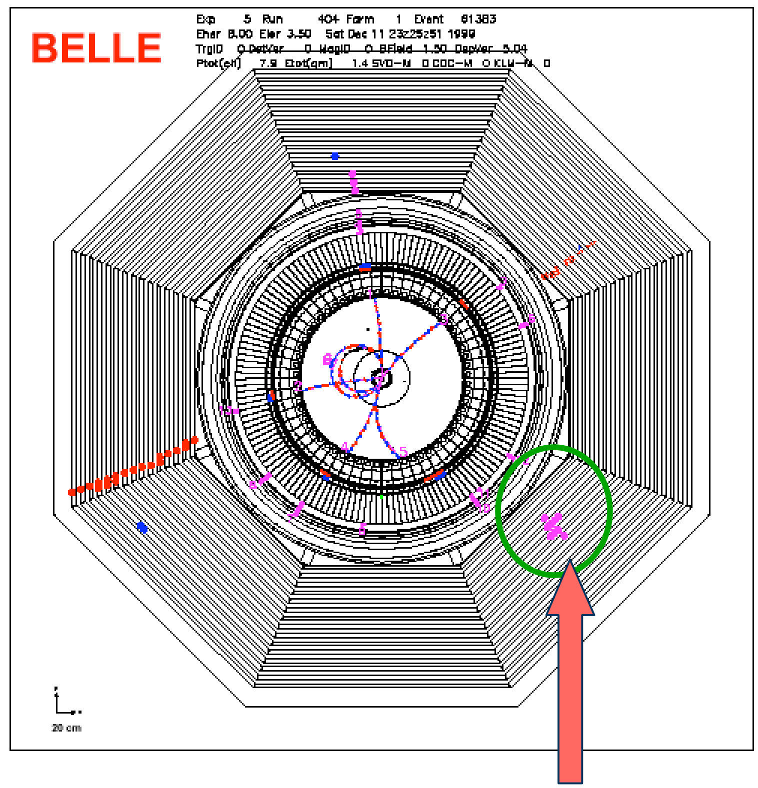
Fully reconstructed



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

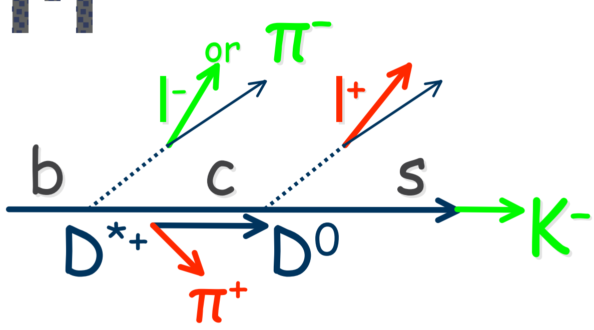
$\sin 2\phi_1$: {charmonium}+K_L tag (CP=+1)





[2332 events, purity ~0.60]

Flavor tagging: all remaining particles



- 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, □>99%

- wrong-tag fraction **w**

  classify events based on expected **w** (MC) - 6 bins.

  (actual **w** -B^0 mixing amplitude in data)>

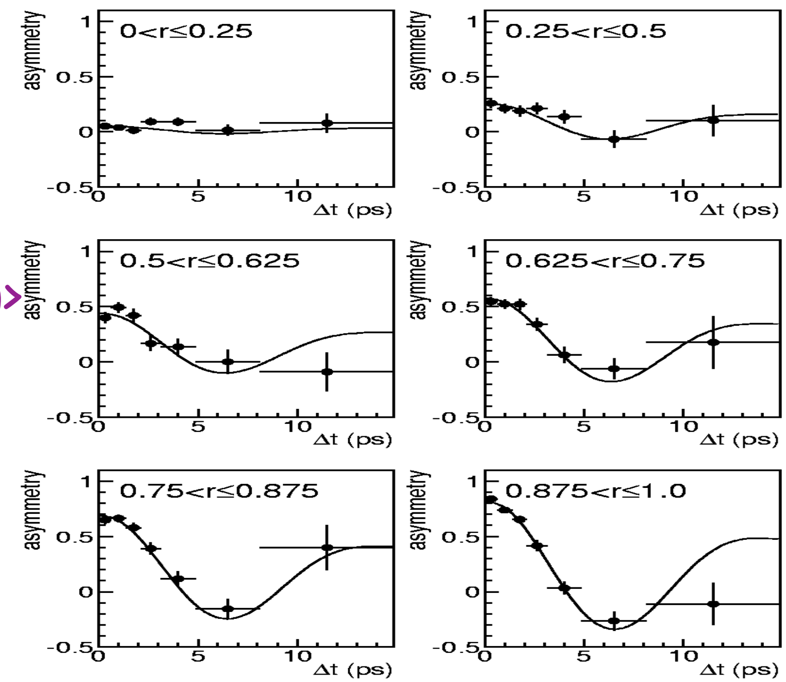
- effective efficiency

  = □(1-2**w**): net (28.7±0.5)%

Flavor-specific B^0

($B \to D^{*+}$ l □)

mixing amplitude <-> **w**



Δz: vertex reconstruction

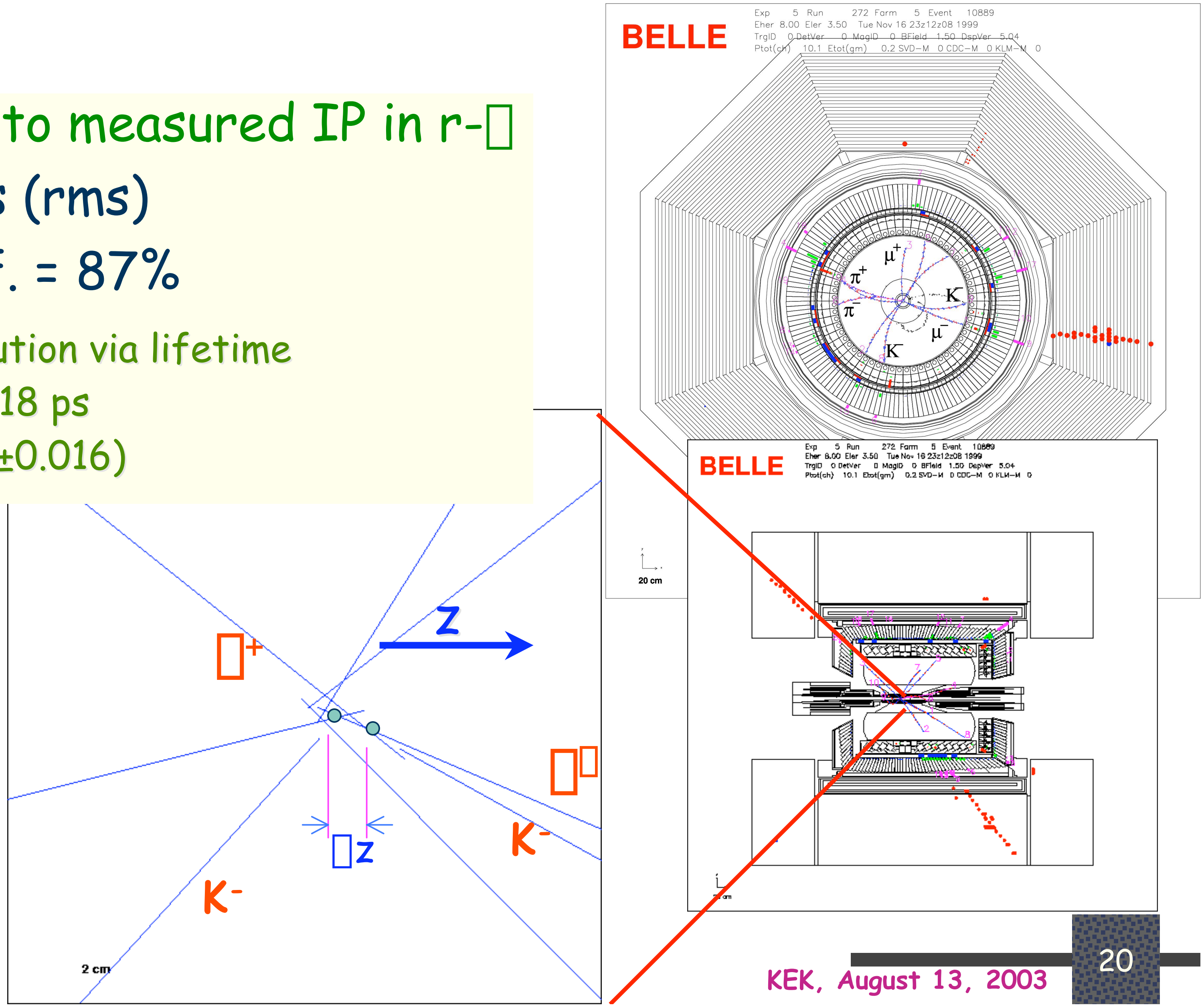
Constrained to measured IP in r-φ

- $\sigma_{\Delta t}$~1.43 ps (rms)
- Overall eff. = 87%

Validate resolution via lifetime

τ_{B0} = 1.551±0.018 ps

(PDG02: 1.542±0.016)

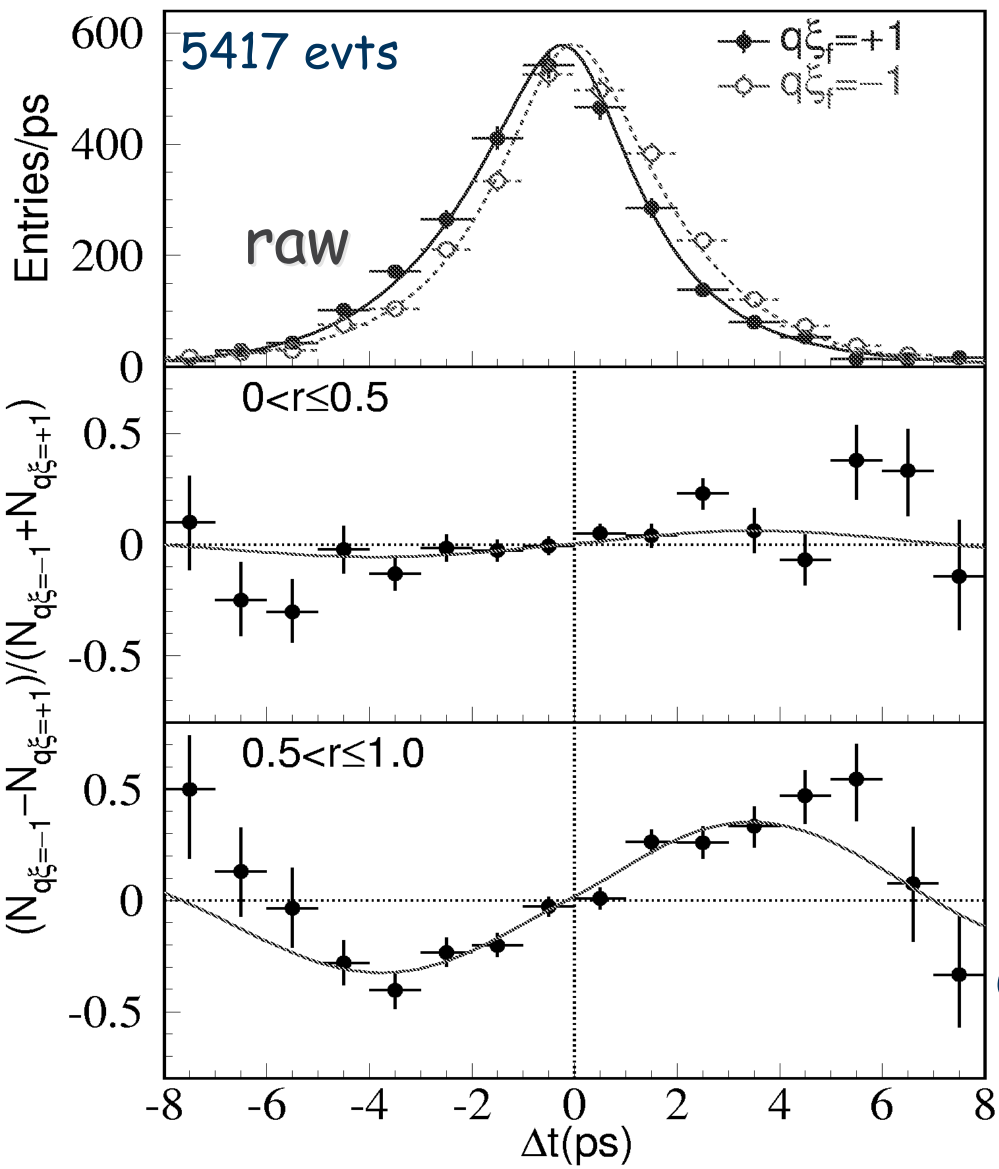


Fitting Δt distribution

- use data wherever possible to validate
- unbinned maximum likelihood fit, includes
  - signal root distribution (analytic)
  - wrong tag fraction (const)
    - flavor-specific tags -> w, mixing oscillation (Δm_d)
  - background: right & wrong tag (MC, parametrized)
  - detector & tagging Δz resolution
    - parametrized,evt-by-evt - params from lifetime fits, validate by measuring τ_B, τ_D, Δm_d
    - accounts for detector resolution, poorly measured tracks, physics (e.g. charm), approximation of $\Delta t = \Delta z / \beta\gamma c$

Checks- separate opp CP tags, verify null signal for flavor-specific tags

Measurement of sin2□$_1$ with 142 fb^{-1}



sin2□$_1$= 0.733±0.057±0.028

Poor tags

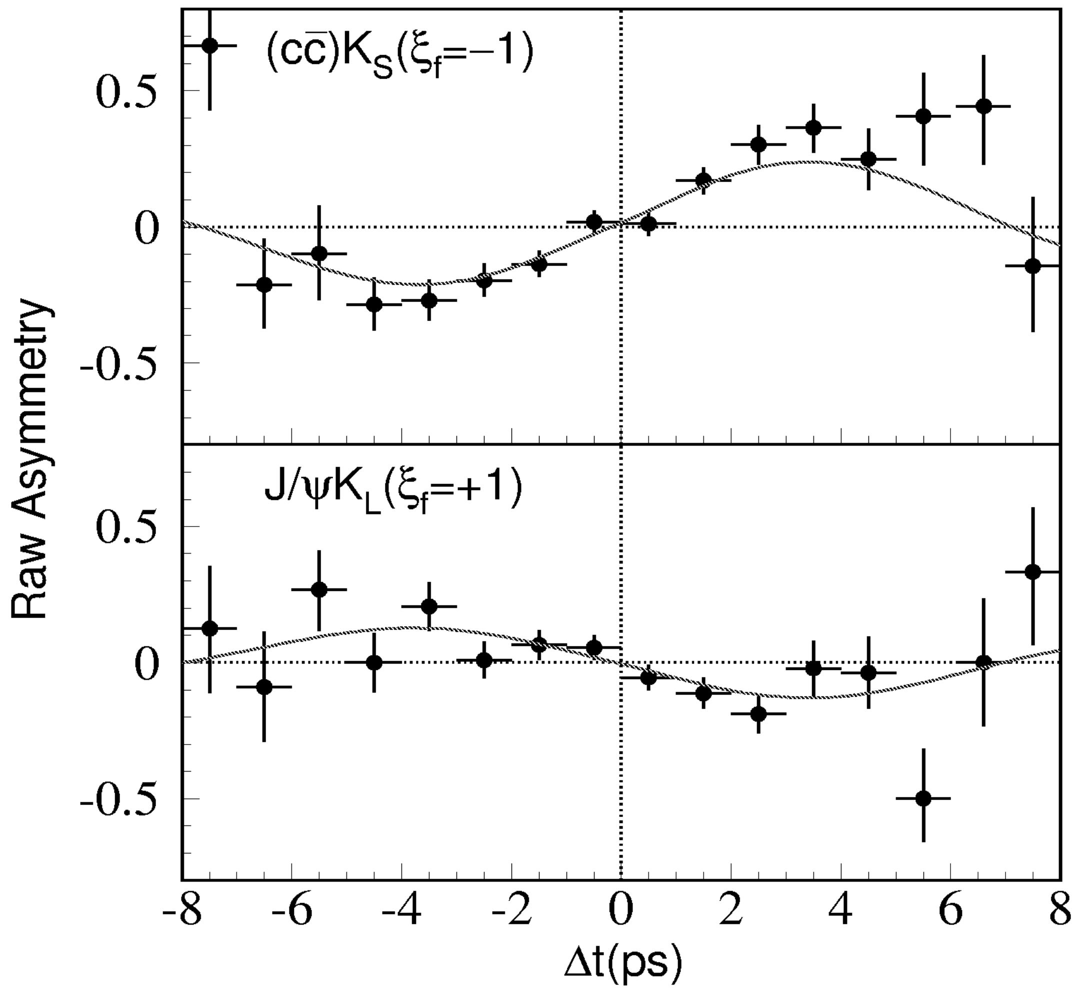
consistent with no direct CPV.

Good tags

BELLE-CONF-0353

Separate CP odd/even

Raw asymmetry (all r-bins)



CP = -1 sample

$\sin 2\phi_1$ = 0.73±0.06

CP = +1 sample

(B^0->J/ψ K_L)

$\sin 2\phi_1$ = 0.80±0.13

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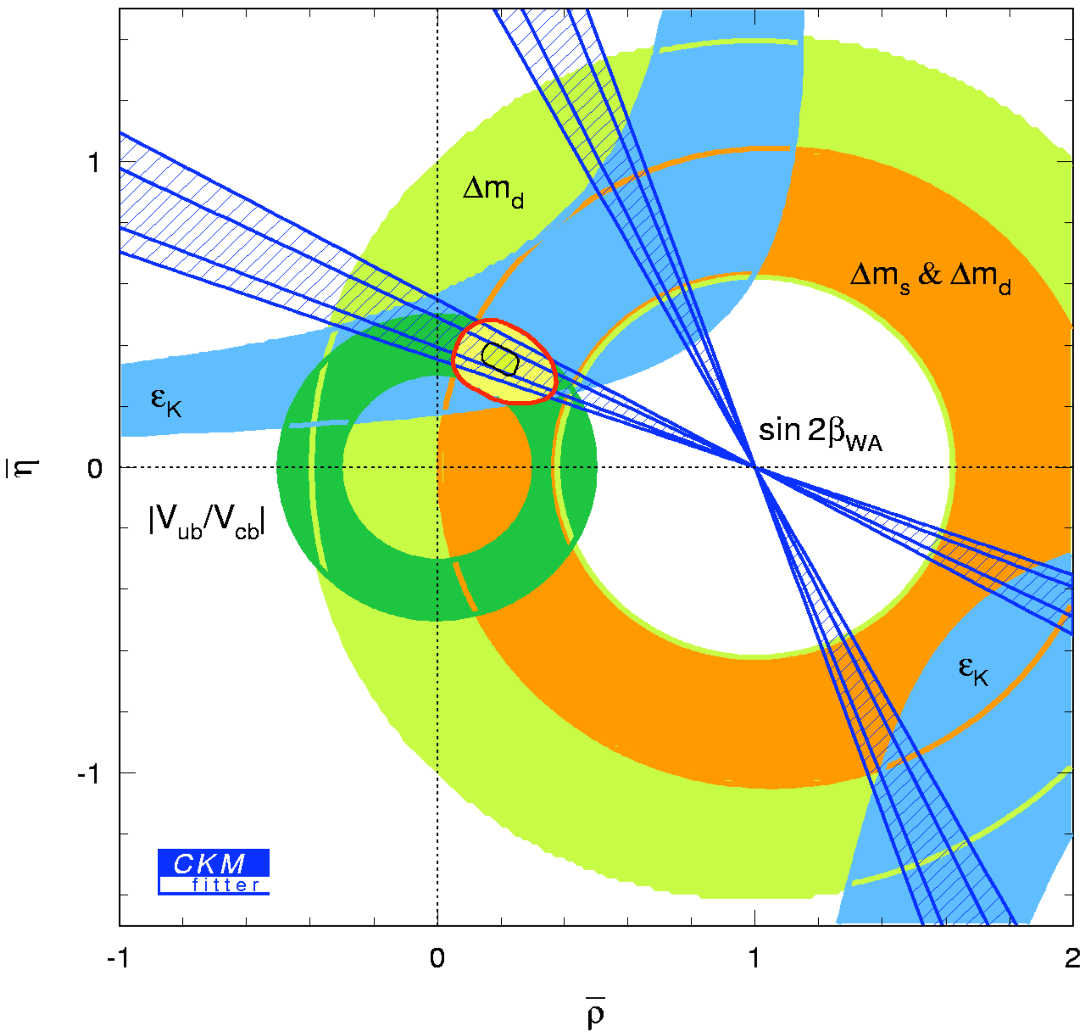
Latest average from {cc}K



$\sin 2\phi_1$ (Belle 2003, 140 fb^{-1})
$=0.733\pm0.057\pm0.028$

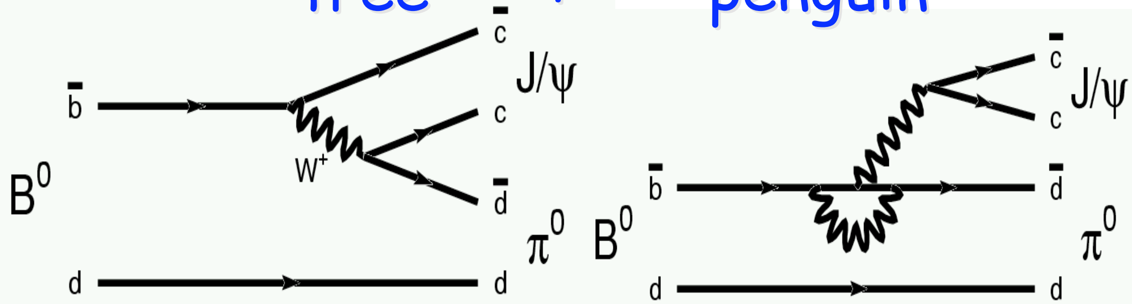
$\sin 2\phi_1$ (BaBar 2002, 81 fb^{-1})
$=0.741\pm0.067\pm0.033$

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

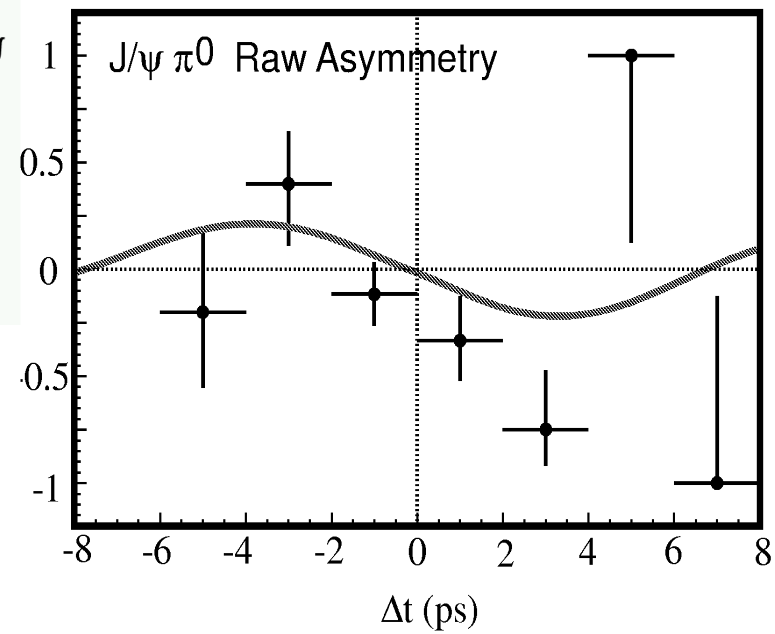
$=0.736\pm0.049$

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

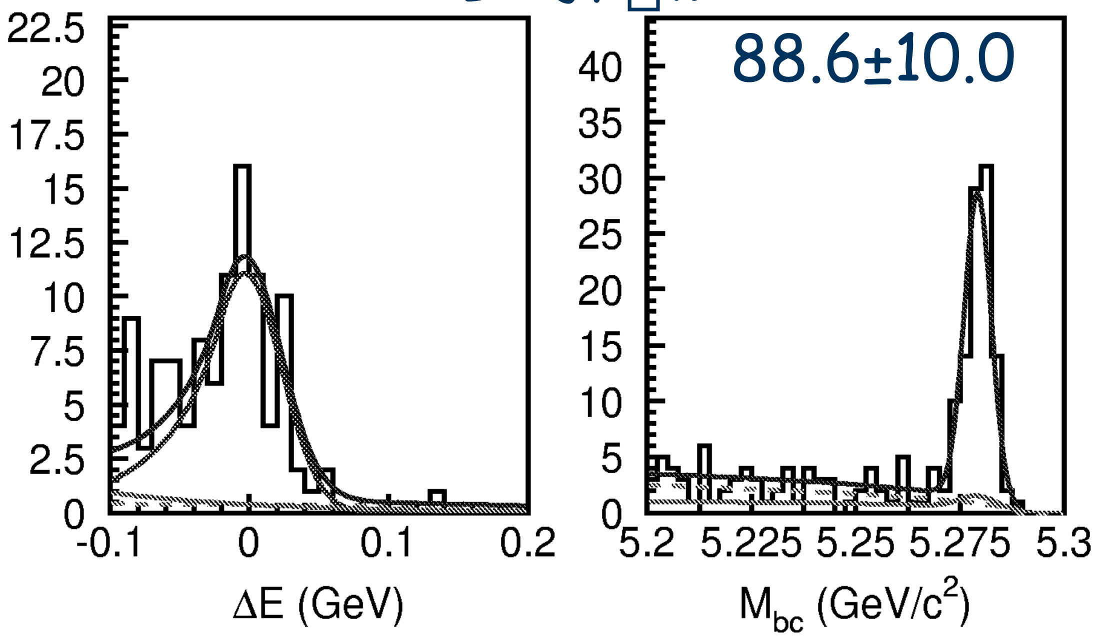
tree + penguin



(relative amplitudes, strong phase not known)



B->J/ψπ^0



S=-0.72±0.42 (stat. only)

(expect $-\sin 2\phi_1$ if penguin is small)

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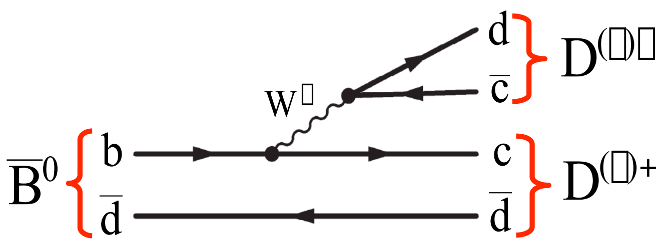
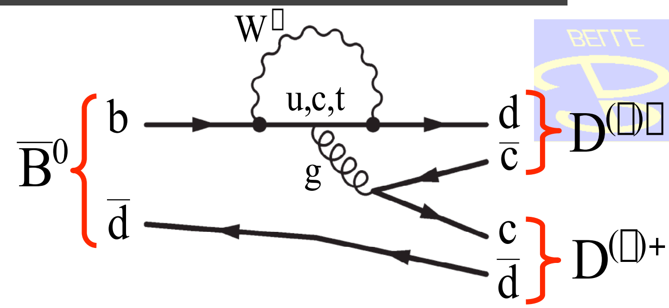
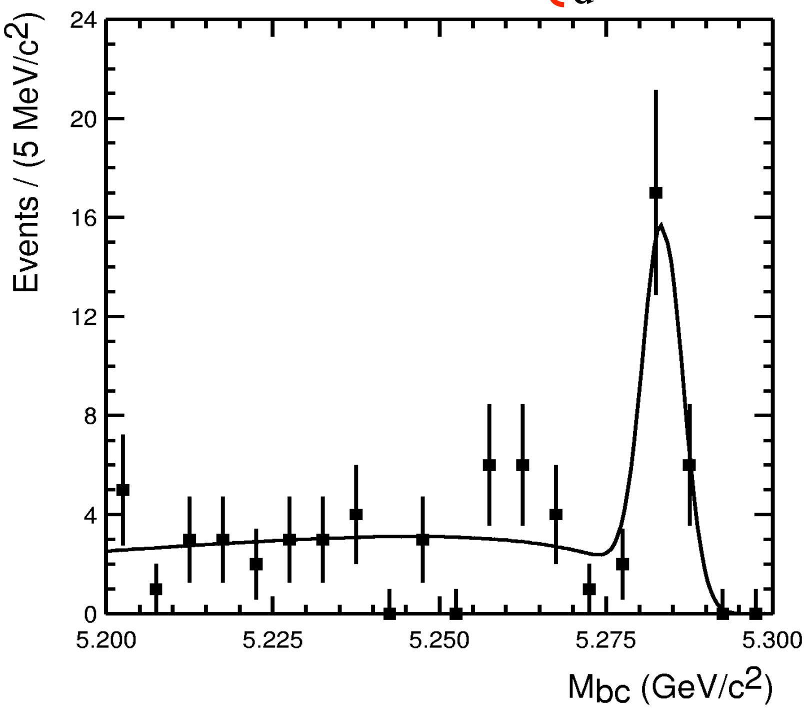
b->{c $\bar{c}$ d}: observation of $D^+ D^-$







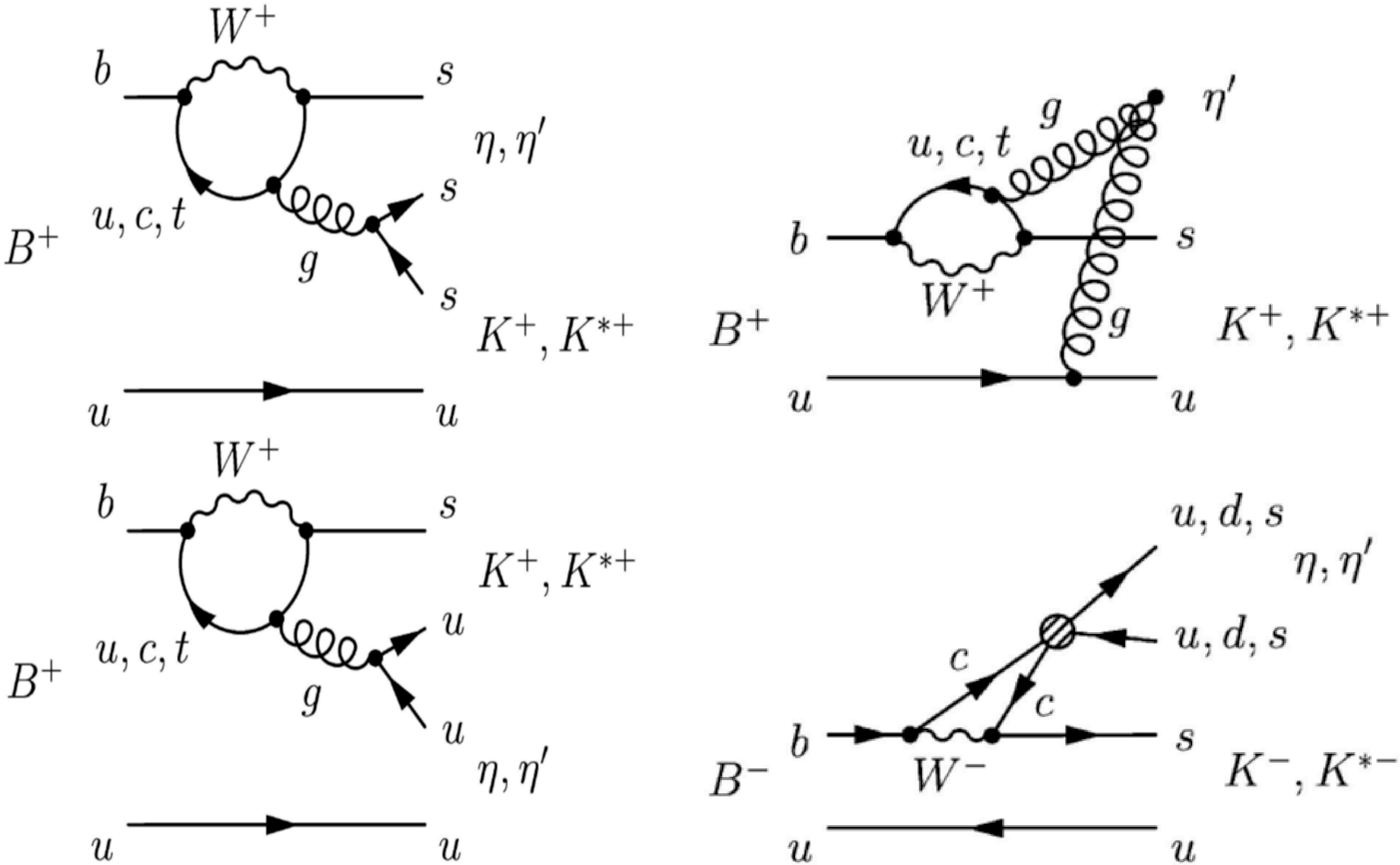
- Yield : 24.3 ± 6.0
- Significance : 5.0
- Efficiency : 7.95 %
- $B= (2.46 \pm 0.61 \pm 0.42) \times 10^{-4}$

May be used in the future for time-dependent CP asymmetry measurements

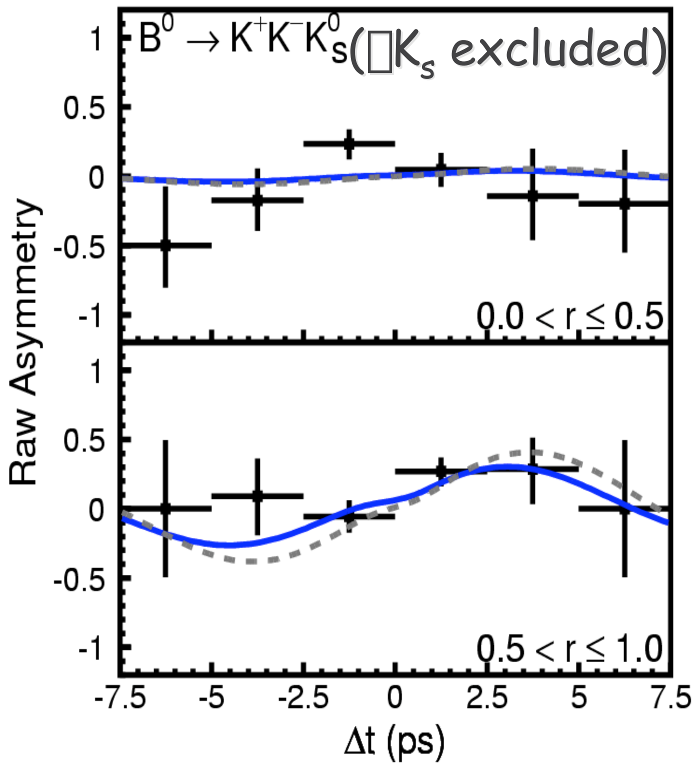
More time-dependent sin2ϕ_1 – or new physics

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

In the absence of New Physics, S = sin2ϕ_1

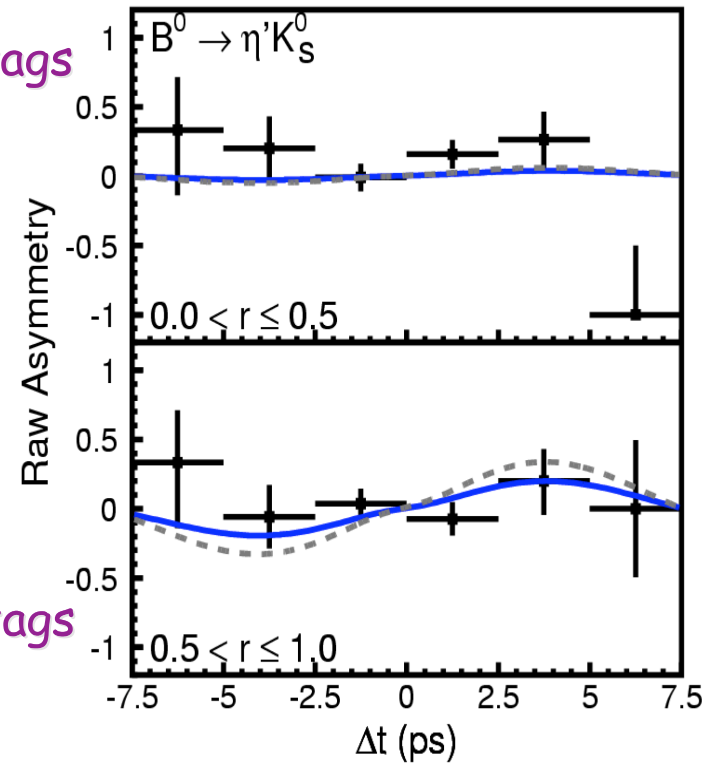


Time-dependence in b->s penguins:



poor tags

good tags



$S = 0.51 \pm 0.26 \pm 0.05 \, {}^{+0.18}_{-0.00}$

3rd error: due to uncertainty in CP content.

(A=-0.01±0.16±0.04)

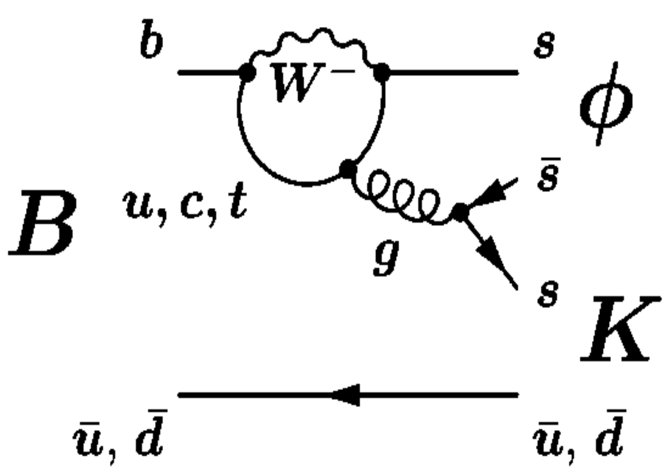
$S = 0.43 \pm 0.27 \pm 0.05$

BELLE-CONF-0344

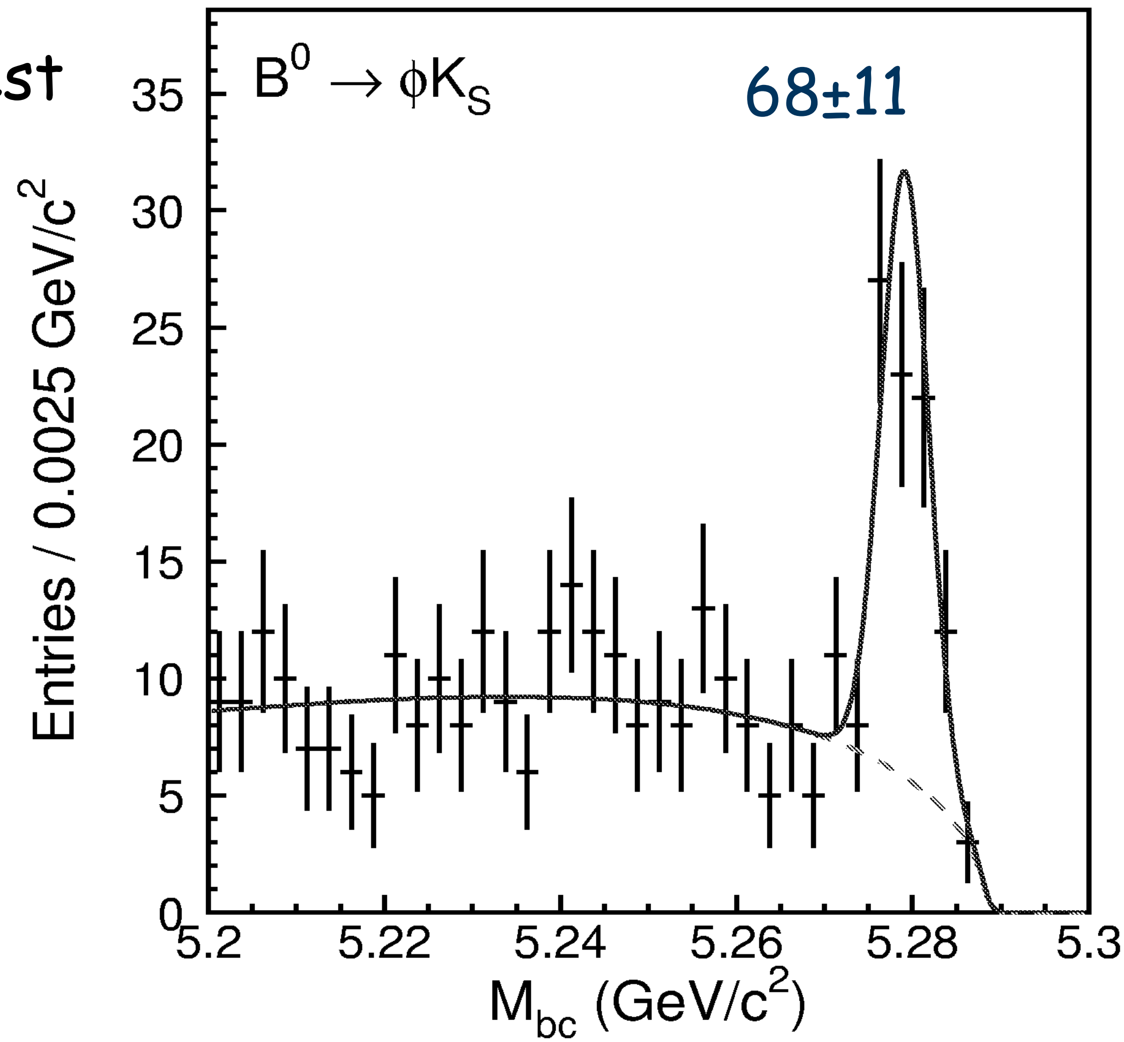
[sin2□$_1$(world average) = 0.736±0.049]

b->s penguins: search for new physics

Theoretically cleanest example:



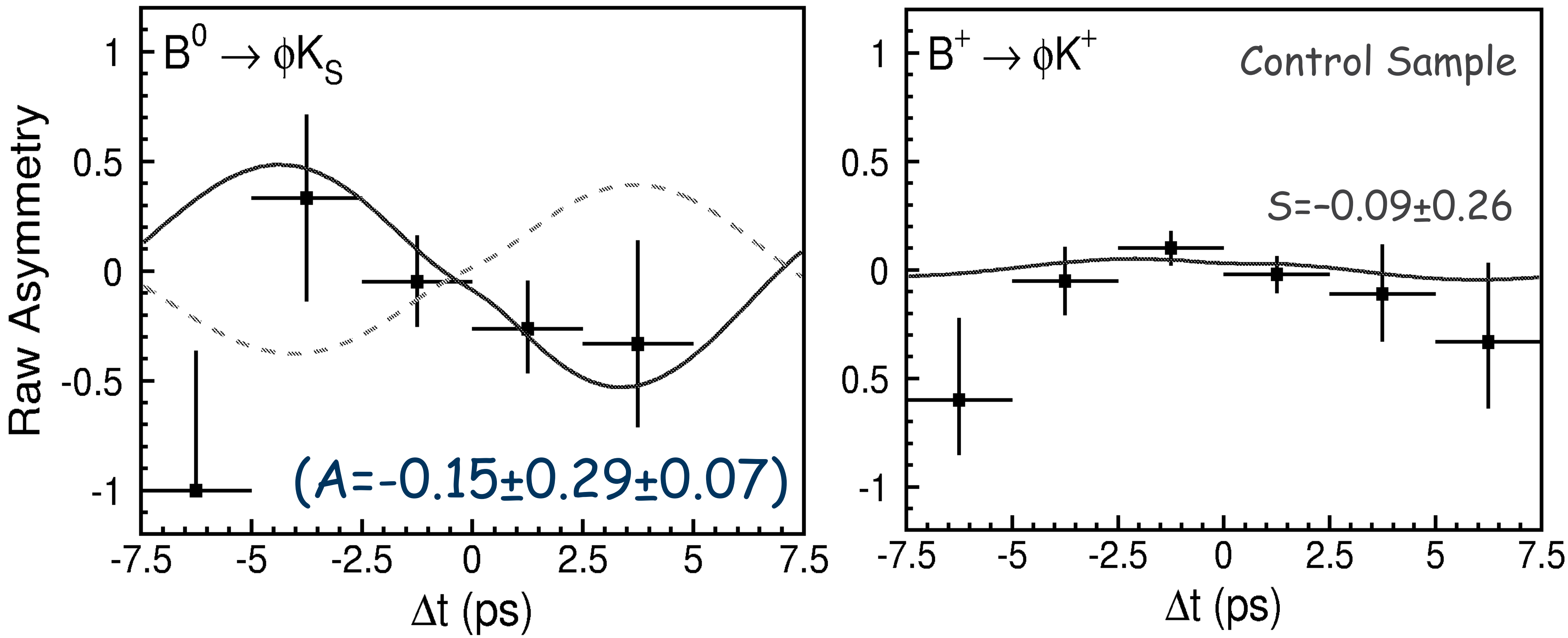
Belle (78 fb^{-1}):
S=-0.73±0.64±0.22



In the absence of New Physics, $S=\sin 2\phi_{1eff} = \sin 2\phi_1$

CP Asymmetry in B->□K_S

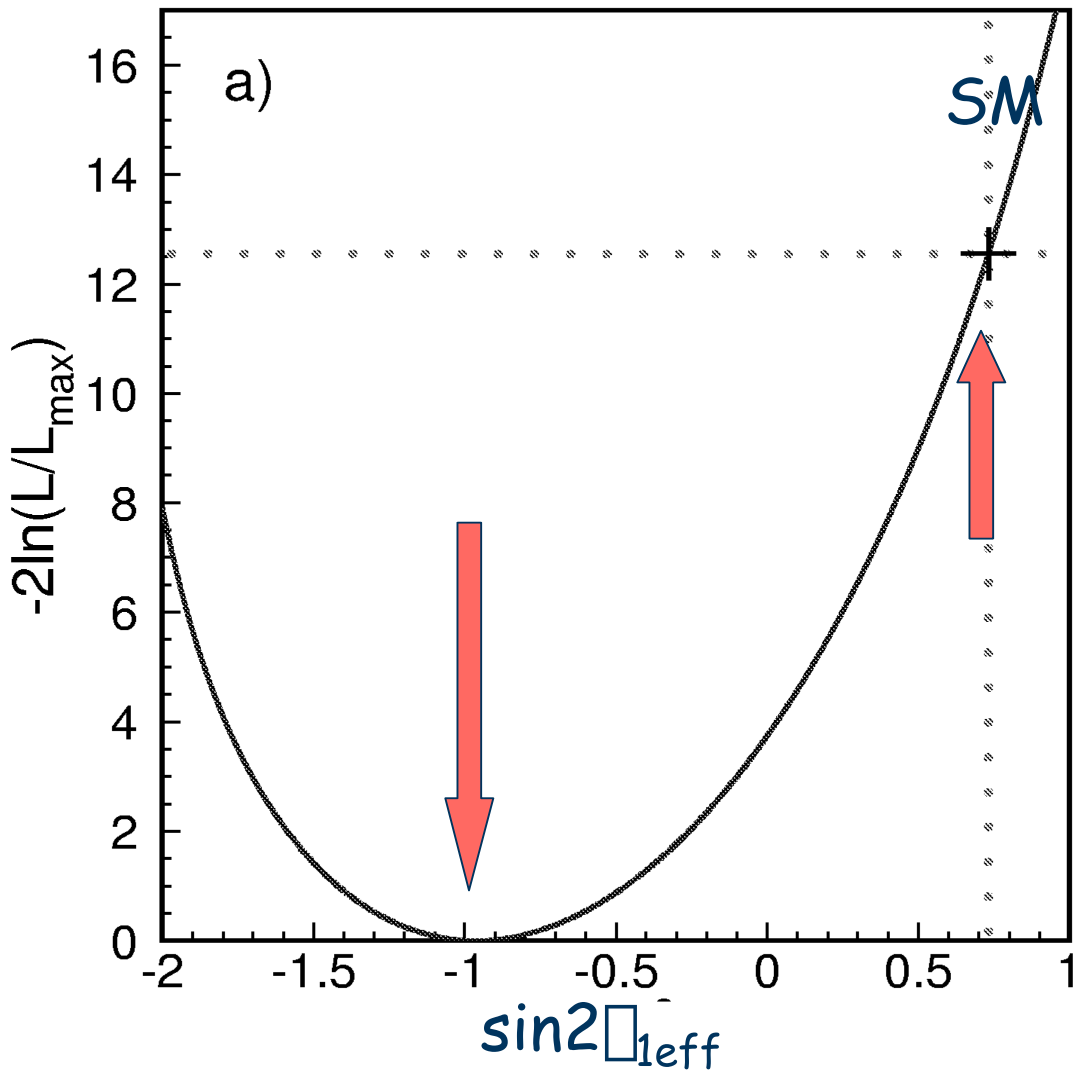
BELLE-CONF-0344



$\sin 2\square_{1eff} = -0.96 \pm 0.50^{+0.09}_{-0.11}$ ← differs by 3.5□

[Current $\sin 2\square_1$(world average) = 0.736±0.049]

Probability & statistics



Feldman-Cousins treatment including systematic from CP in the background finds this value ruled out at 99.95% CL or 3.5σ

Systematic uncertainties

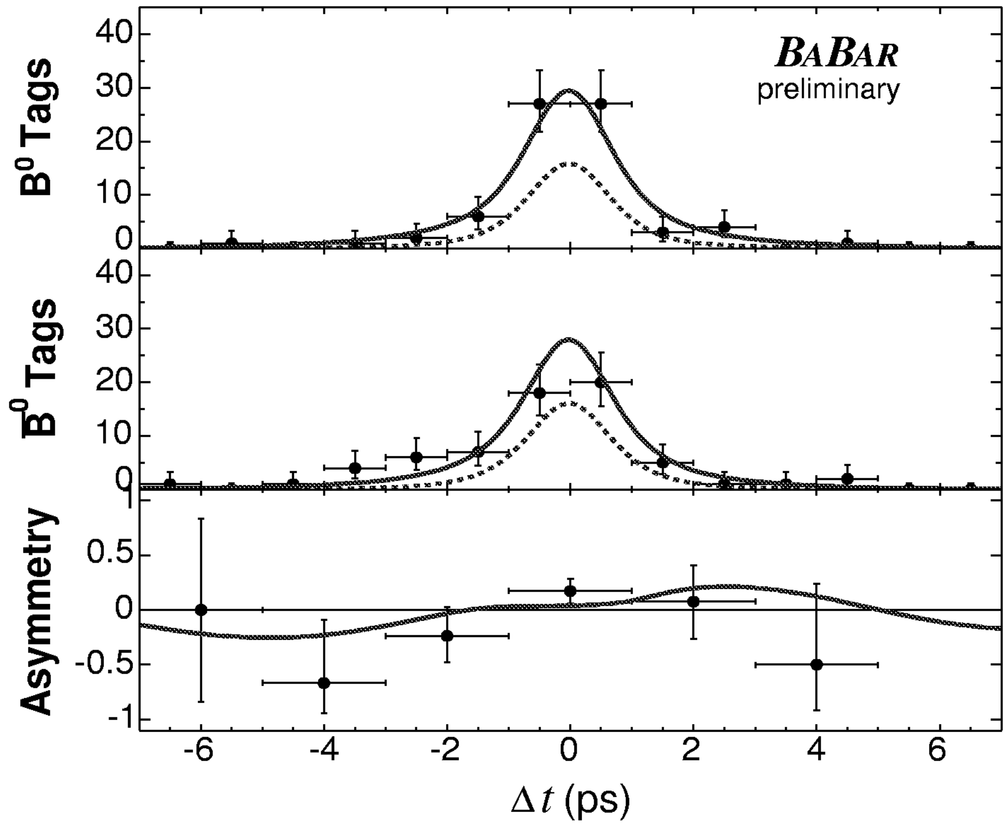
	S	A
Fitting near |S|=1	+0.06 −0.00	–
backgnd $K^+K^-K_s$, $f^0(980)K_s$	+0.00 −0.08	±0.04
background fraction-other	±0.05	±0.04
Vertex algorithm	±0.02	±0.05
Total	+0.09 −0.11	±0.07

Correlation between A and S ? A=-0.15 ±0.29±0.07

If A is fixed to zero, S=-0.99±0.50

BaBar result ϕK_S

BaBar 2003: 110 fb^{-1}



(A=0.38±0.37±0.12)

$\sin 2\phi_{1eff}$ = +0.45±0.43±0.07

BaBar B-> ϕK_S Systematics

81 fb^{-1}: $\sin 2\phi_{1eff} = -0.18 \pm 0.51 \pm 0.09$

↓

110 fb^{-1}: $\sin 2\phi_{1eff} = +0.45 \pm 0.43 \pm 0.07$

Data size increased and was reprocessed. Extensive checks with data and Toy MC. The large change is attributed to a 1_ statistical fluctuation.

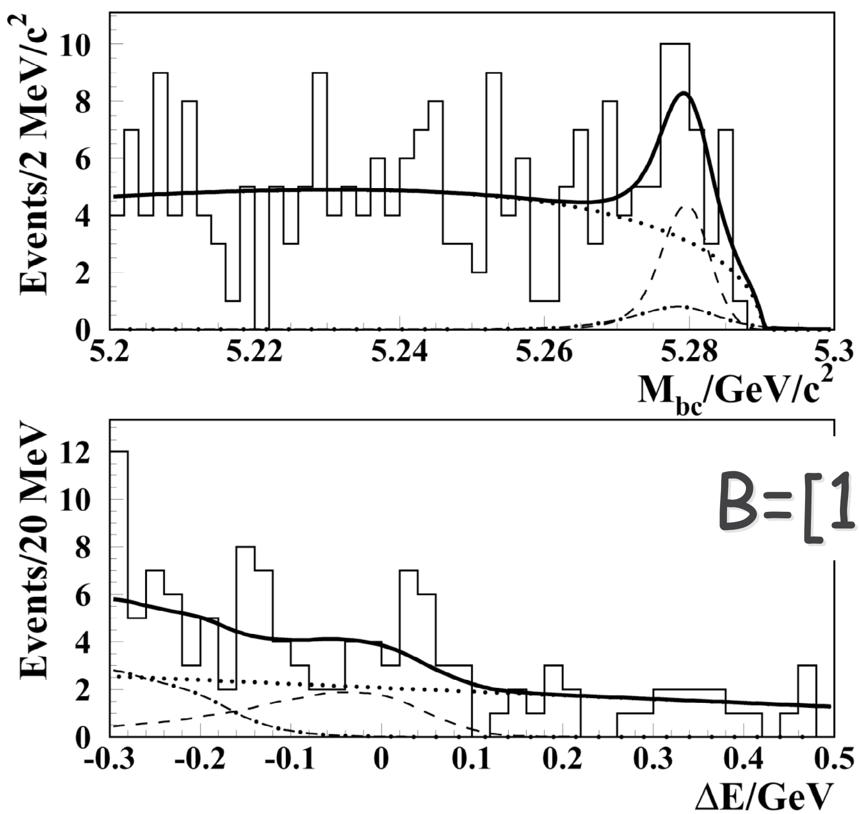
BaBar B-> □K_S Systematics

Systematic uncertainty due to	S	C
Fit bias	0.04	0.05
Event yield	0.01	0.05
Parametrization of Δt resolution	0.03	0.02
Background composition/CP asymmetry	0.03	0.05
m_{ES} background parameterization	0.02	0.05
Uncertainties in the SVT alignment	0.01	0.01
Beamspot position	0.01	0.01
PDFs for the event yield in signal and background	0.004	0.04
Potential S-wave contamination	0.002	0.015
$B^0/\bar{B}^0$ efficiency difference	0.002	0.02
Doubly-Cabibbo-suppressed decays	0.009	0.027
Total	0.07	0.12

Observation of $B^0 \to \pi^0\pi^0$

Gronau, London PRL 65, 3381 (1990): isospin analysis of $B \to \pi\pi$ to obtain ϕ_2 without time-dependence

$\pi^0\pi^0$ is most difficult step.

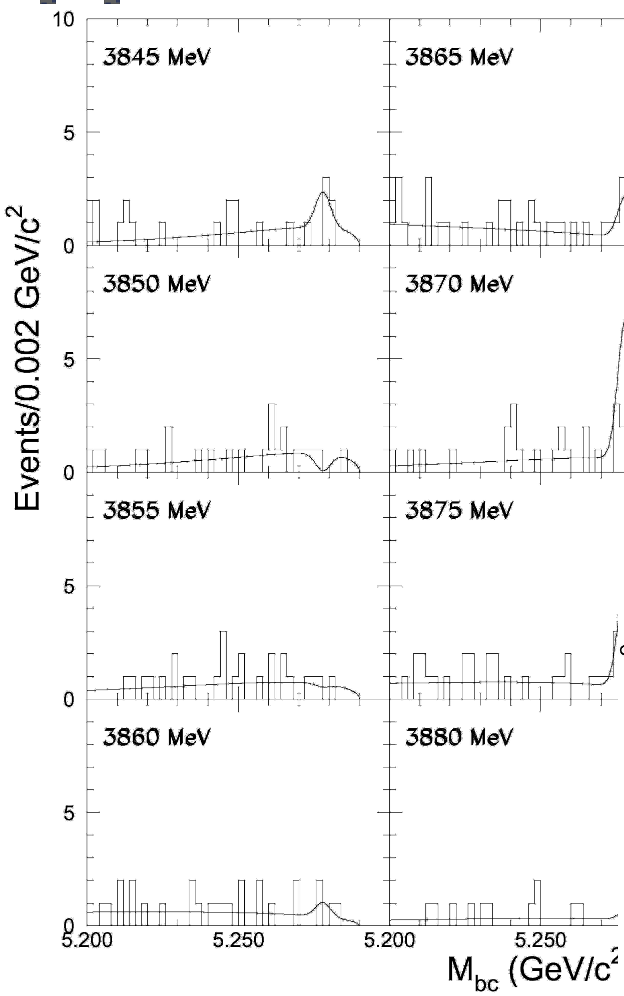


$B=[1.7\pm0.6\pm0.2]\times10^{-6}$

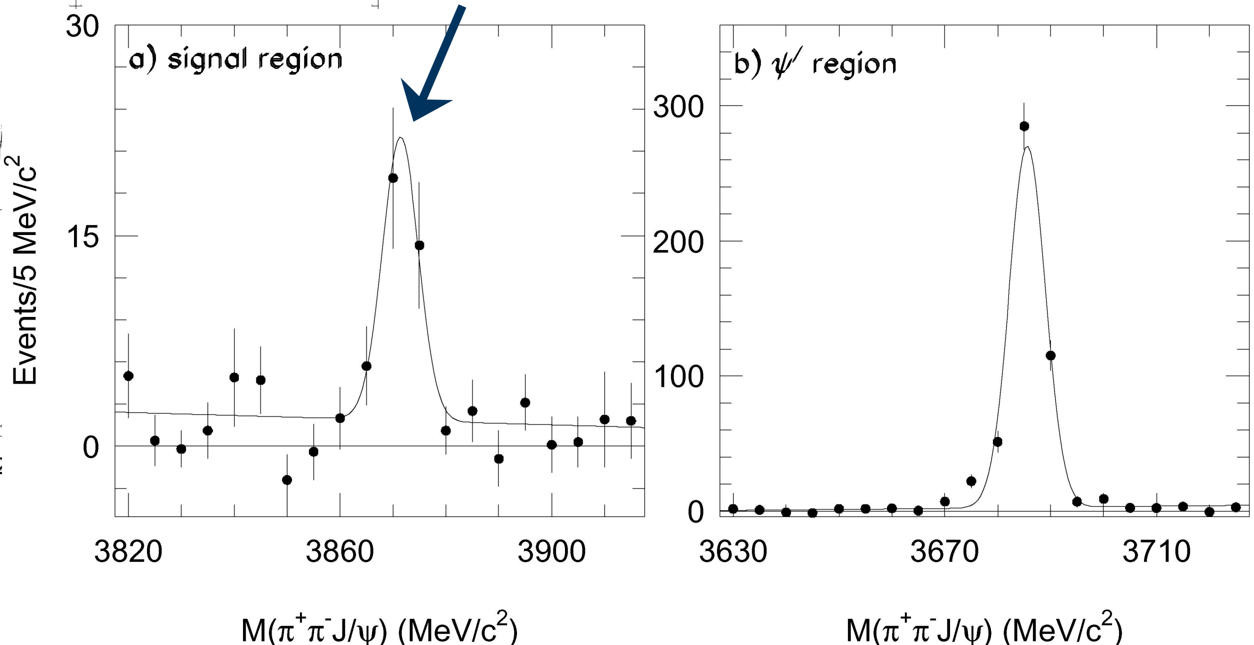
Charm: observation of new charmonium state

in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$

bins of $\pi^{+}\pi^{-}J/\psi$ mass



$M = 3871.8 \pm 0.7 \pm 0.4\ MeV/c^2$



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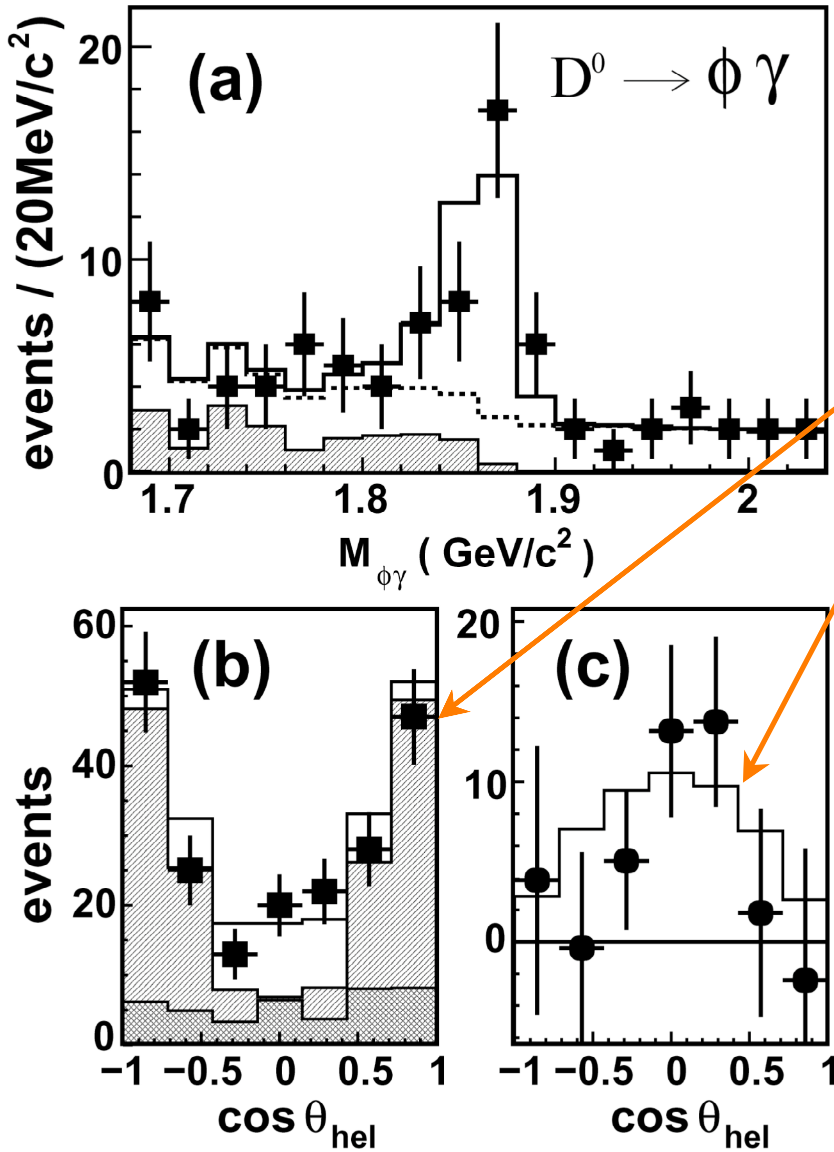
Observation of first radiative D decay



$D^0 \to \phi\gamma$ ($\phi \to K^+K^-$)

- large bg from $D^0 \to \phi\pi^0$ (also first observation) distinguish by $\phi \to KK$ helicity angle distribution

$B = [2.60 ^{+0.70}_{-0.61} {}^{+0.15}_{-0.17}] \times 10^{-5}$

BELLE-CONF-0346

Summary

Belle in August 2003:

- KEKB L= $1.06\times10^{34}cm^{-2}s^{-1}$ <- @design! ($1\times10^{34}cm^{-2}s^{-1}$)
- 152M B pairs: sin2ϕ_1 has become a "precision" measurement
- first results on alternative probes of sin2ϕ_1 (or new physics!)
  - B->J/ψ π^0 - penguin may be small (need more data)
  - surprise deviation in B->ϕK_s - 3.5σ - hints of new physics?
  - consistency with SM in other b->sss
- developing sensitivity to ϕ_2, ϕ_3
- observations/hints in many modes, possibly CP in future
- large charm sample - new states, modes, searches for NP

Next

- 500 fb^{-1} by 2005
- Luminosity >@ design
- the CP challenge: just getting started - stay tuned!