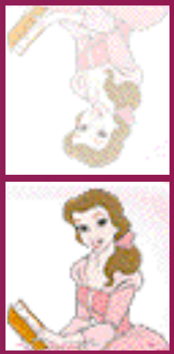
Northern Kentucky University April 14, 2004

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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University of Cincinnati
Belle Collaboration

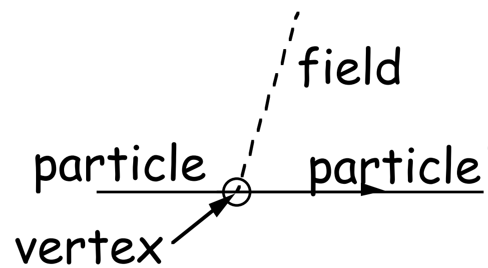
Symmetry of Physical Laws

In 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

- add mass via self-interaction
- interaction strength/probability
  μ "charge" g^2 μ "coupling constant"
- symmetry info in vertex



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)

… but preserves CP symmetry (mostly)

right-handed particles, left-handed antiparticles.

no coupling to LH particles, RH antiparticles.

• violates CP symmetry (a little)

.. but to y2k, 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)

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

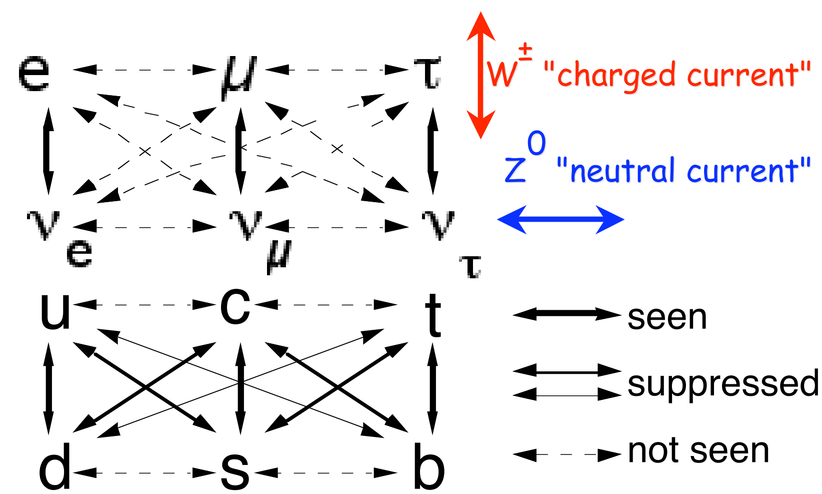
3* generationsx2 typesx2 ea,
stable, but for weak interaction

*generations distinguished only by mass

Couplings:

- ~universal, no generation x-ing for leptons, quark neutral-current
- for quark charged-current (W): al **Inelegant!!** ox 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



Elegance restored: GIM mechanism

Picture

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

  new doublets u/d' c/s' t/b'

  $\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$

  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)

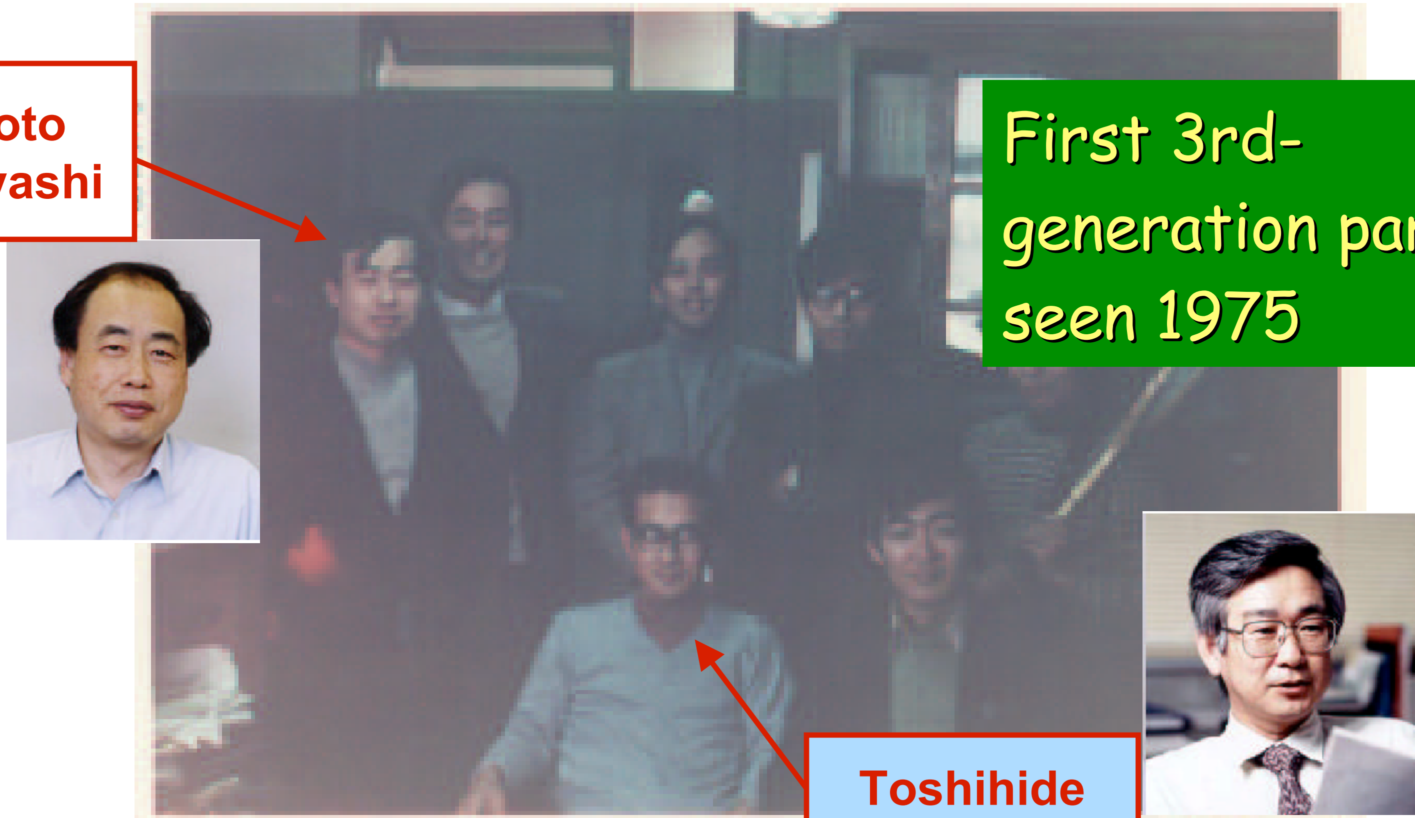
- suppression of flavor-changing neutral currents
- multiplicity of charged current couplings
- AND …….

… 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 × couplings} = $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$ (rows u, c, t; columns d, s, b)

Unitarity →

explicit parametrization(Wolfenstein):

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

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

irreducibly complex

from decay rates,

$\lambda = 0.220 \pm 0.002$

$A = 0.81 \pm 0.08$

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

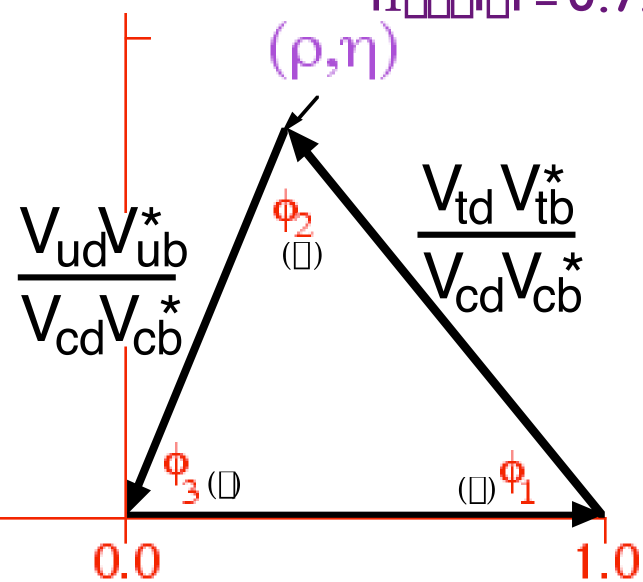
$|1-\rho-i\eta| = 0.79 \pm 0.19$

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

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

↓ [illegible] ↓ [illegible]

(ρ, η): "unitarity triangle"



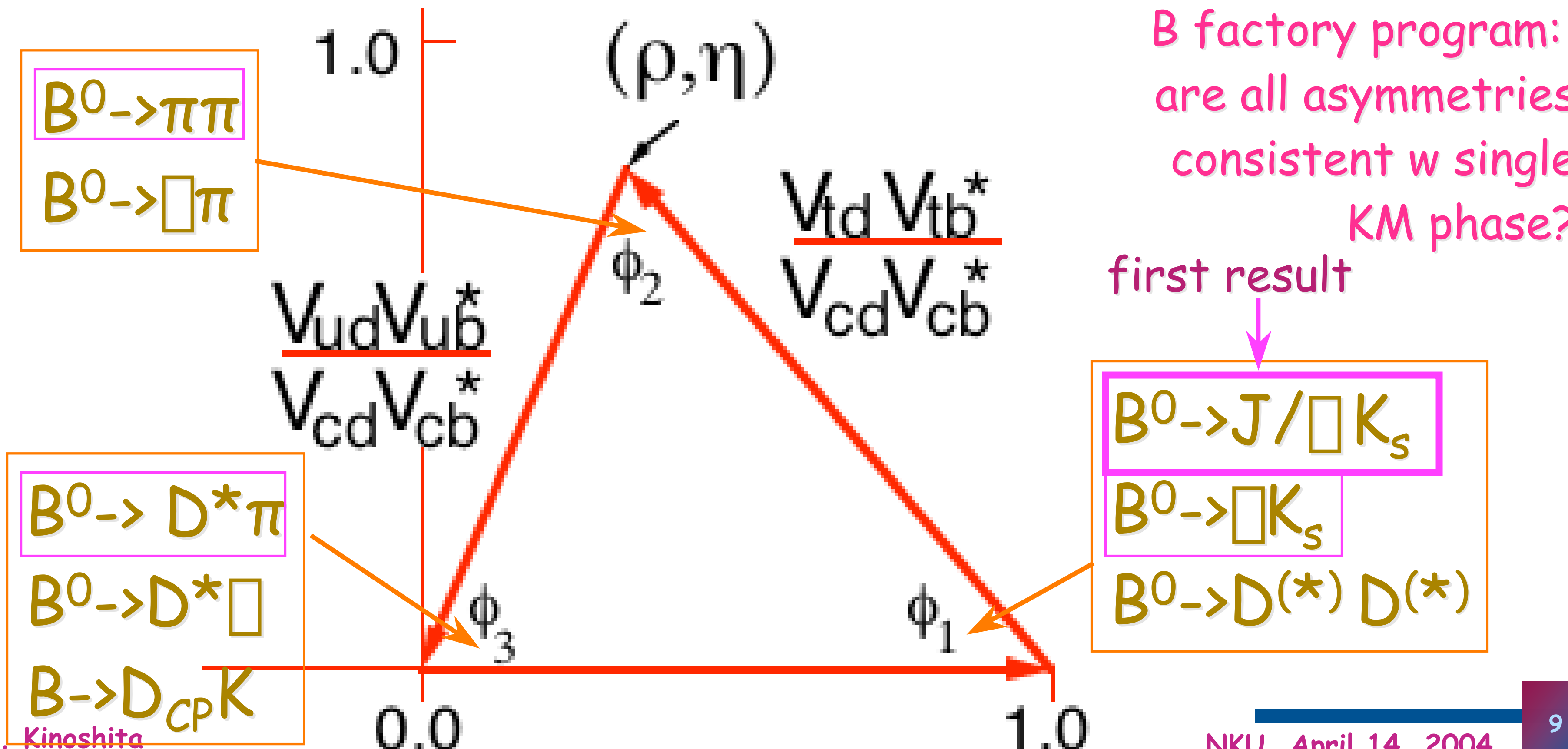
Self-consistent if CKM is correct

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

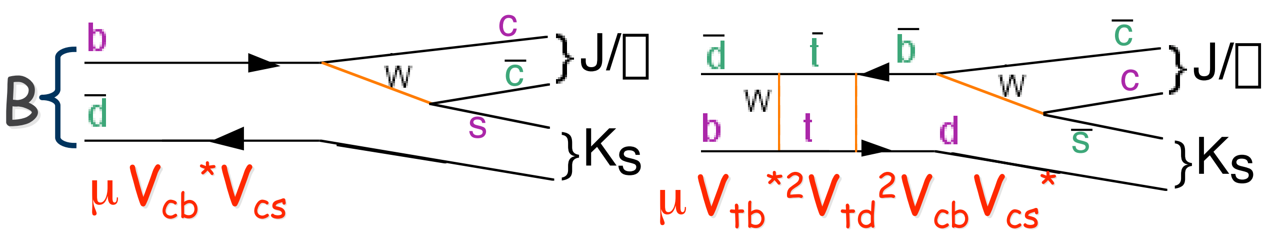


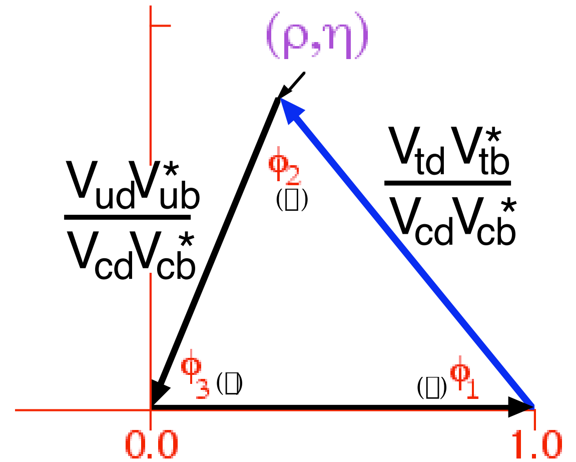
manifestation of complex coupling

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

"indirect" CP asymmetry

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) = $2\phi_1$

Bottom line: CP-dependent oscillation in time:

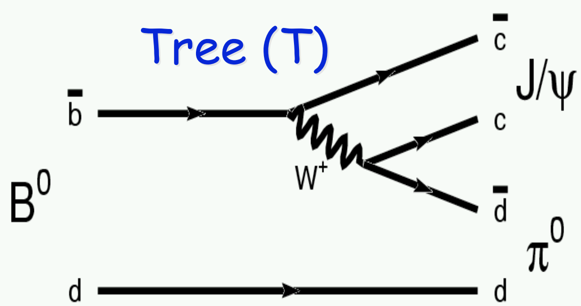
$$\frac{dN}{dt}(B \rightarrow f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b \eta_{CP} \sin 2\phi_1 \sin(\Delta m \Delta t));$$

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

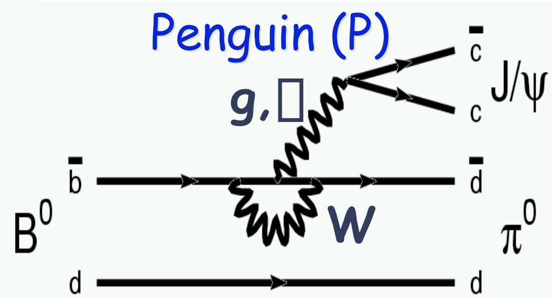
This is only the cleanest, simplest - "golden mode"

CP phenomenology: variation

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



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



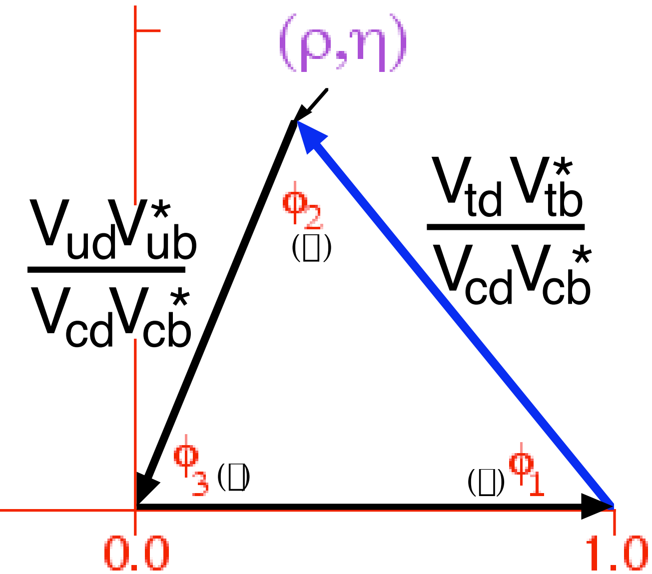
$\propto V_{tb}^{*}V_{td}$

mixing+ "

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

mixing+ "

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



$\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}$ $\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}$

Bottom line: "direct" CP asymmetry possible

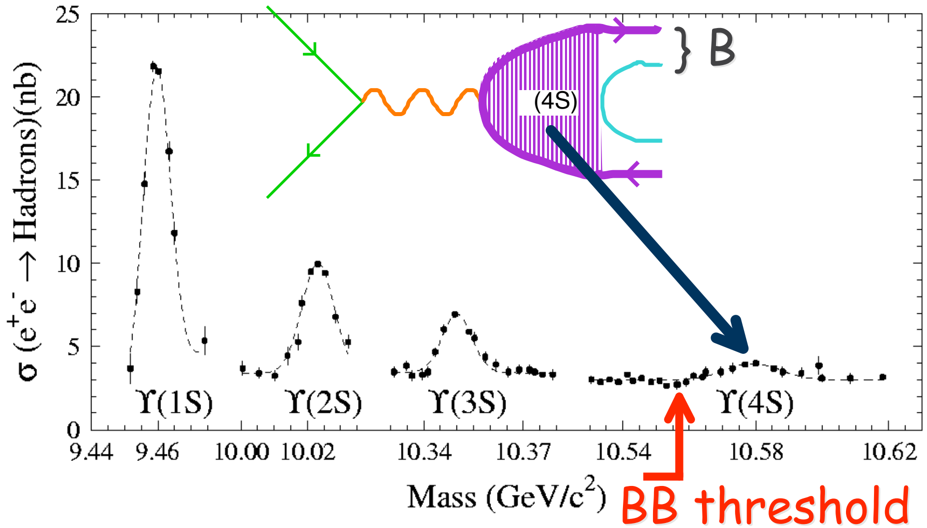
$$q = \begin{pmatrix} +1 \text{if } B_{t=0} = B^0 \\ -1 \text{if } B_{t=0} = \bar{B}^0 \end{pmatrix}$$

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

"direct" asym

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

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



BB threshold

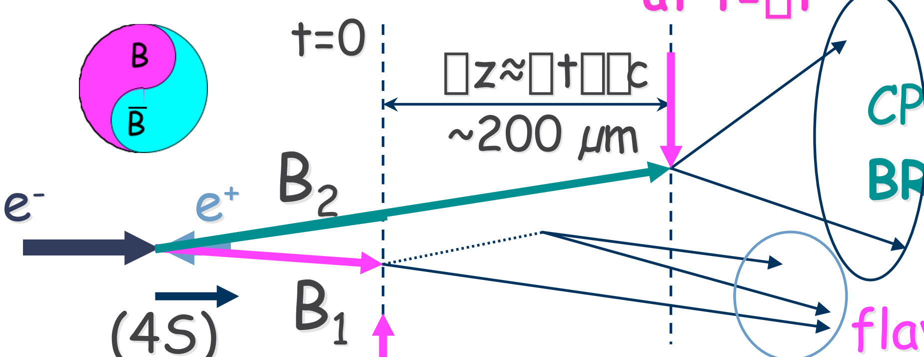
Δt by asymmetric energy e⁺e⁻ -> Υ(4S)

(symmetric Υ(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

2nd decay at t=Δt



CP mode @ t=Δt

BR < 10^{-3}

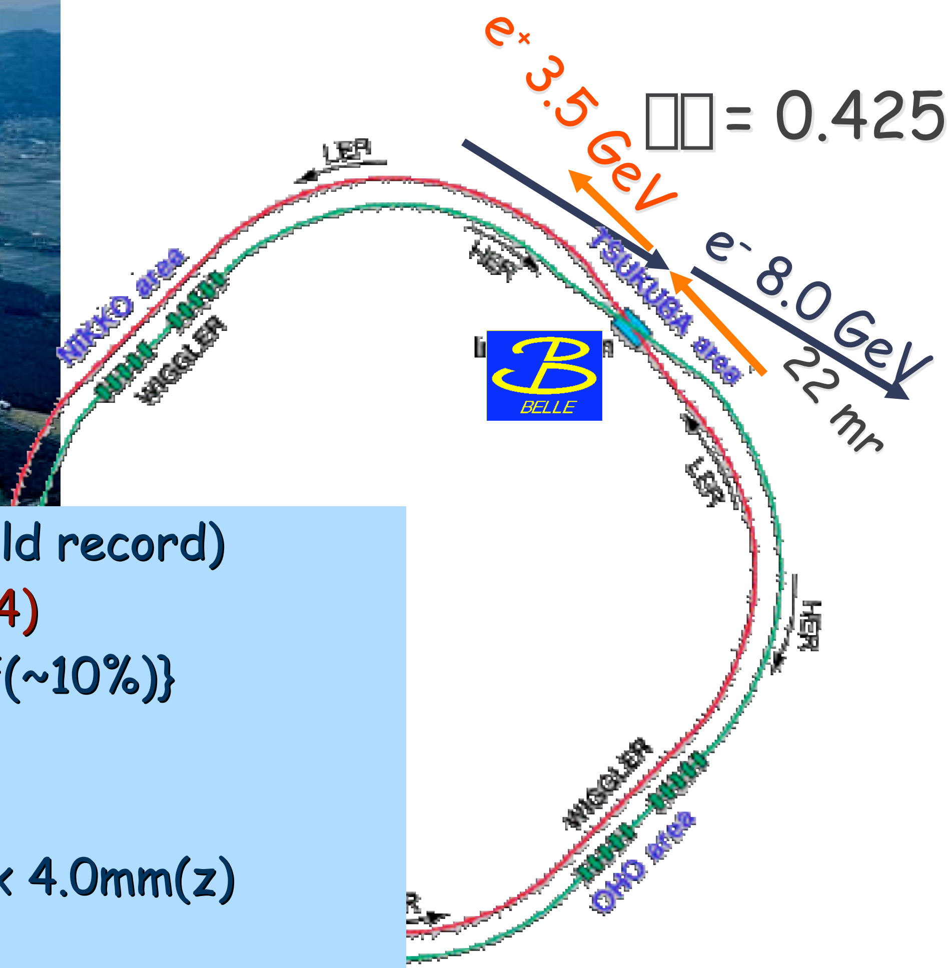
flavor tag @t=0: e, μ, K±, ...

effective eff ~30%

CP=−1, conserved

first B decay (t=0), break CP

Colliding beams: KEKB



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

Data (6/1999–4/2004)

$\int L dt$ = 229 fb^{-1}@{ Υ(4S)+off(~10%)}

(>2.2×10^8 B events)

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

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

The Detector

Charged tracking/vertexing

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

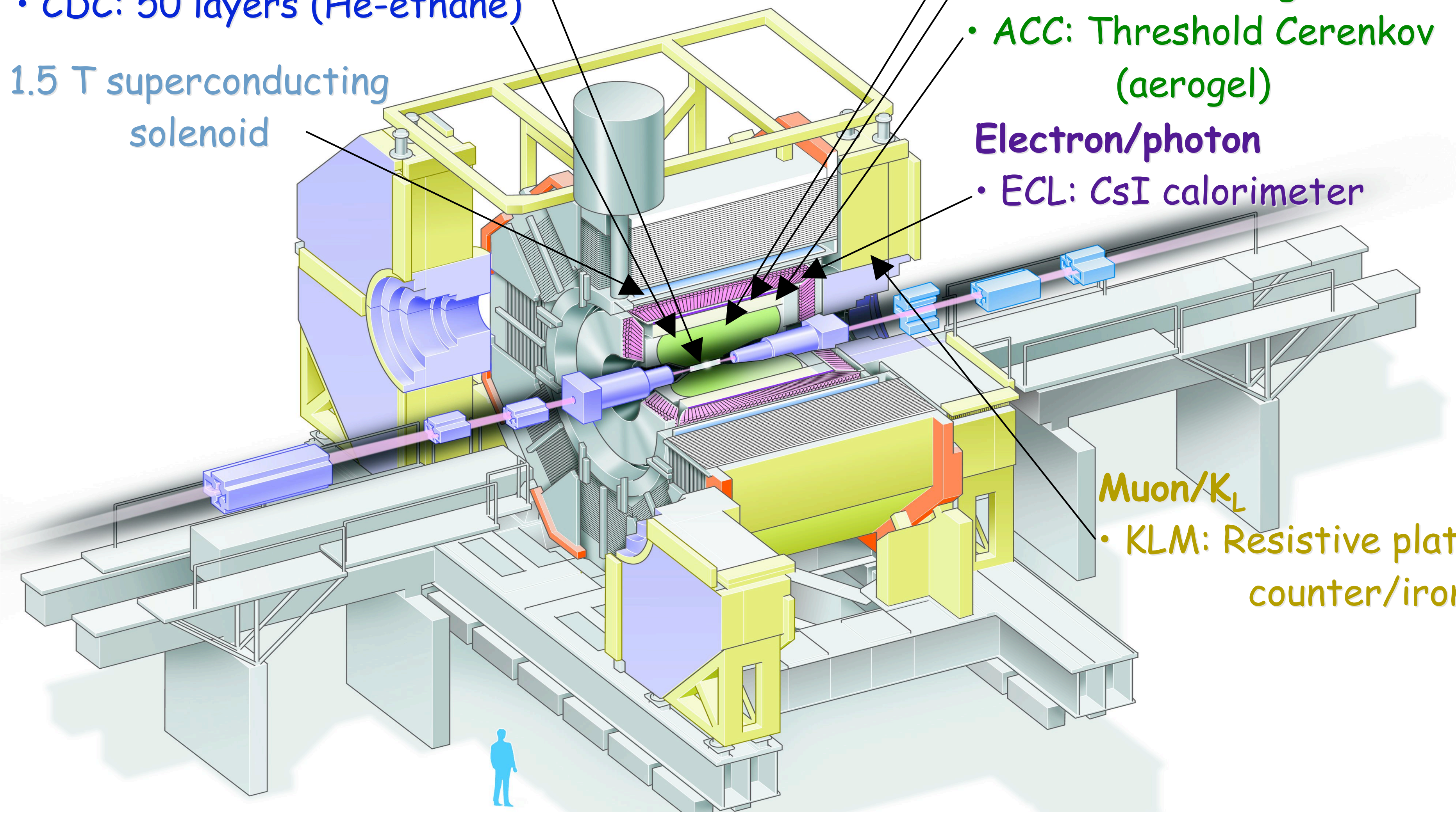
1.5 T superconducting solenoid

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

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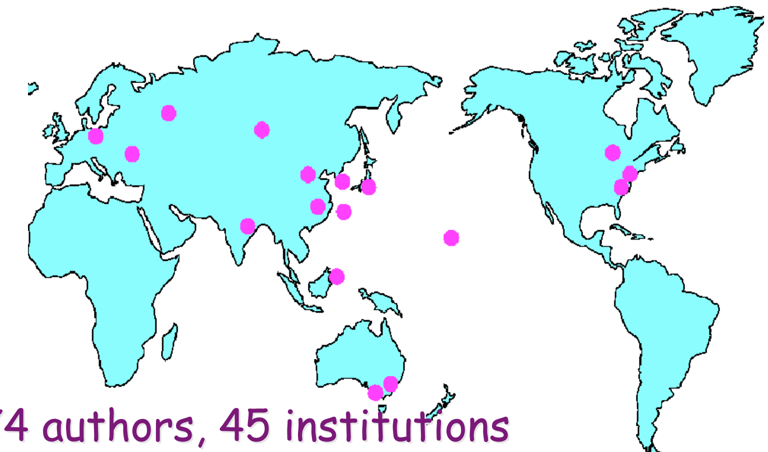

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We present a measurement of the standard model *CP* violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a 10.5 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- 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 $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$.

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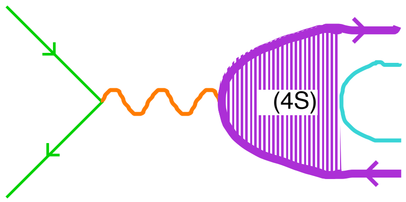
many nations

(numbers vary, every paper)

Belle physics results

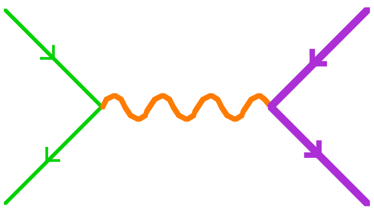
78±2 papers published or in press (1st in 3/2001)

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

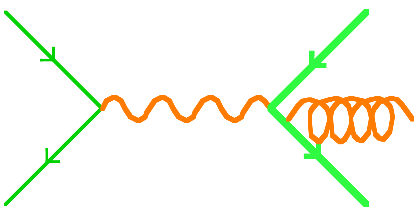


18 - CP asymmetry in B decay

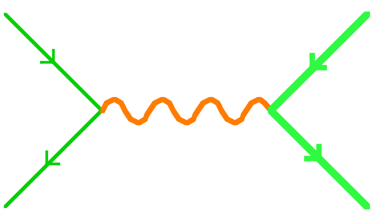
25 - B decay non-CP



8 - charm hadrons



1 - QCD



2 - tau

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

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->$K_s\pi^+\pi^-$}

Charm:

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

time-dependent CP analysis: overview

1) *CP* final state reconstruction

exploit

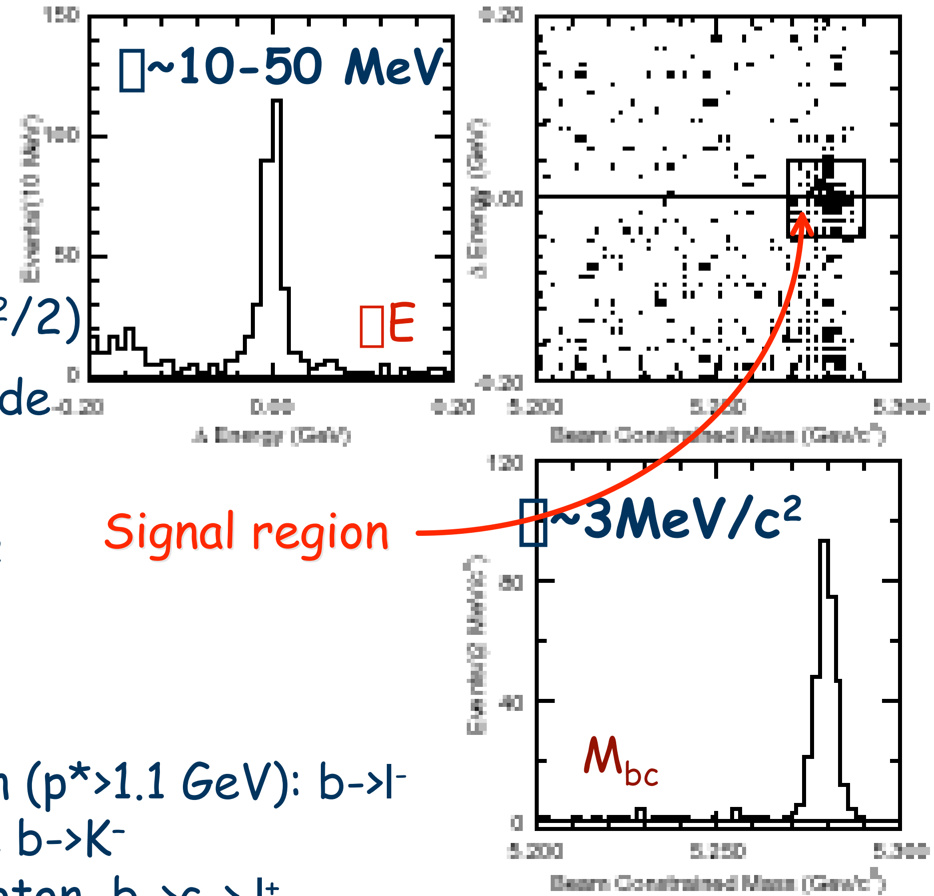
- exclusive pair production of B
- narrow resolution of collision energy

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

σ~10-50 MeV, depending on mode

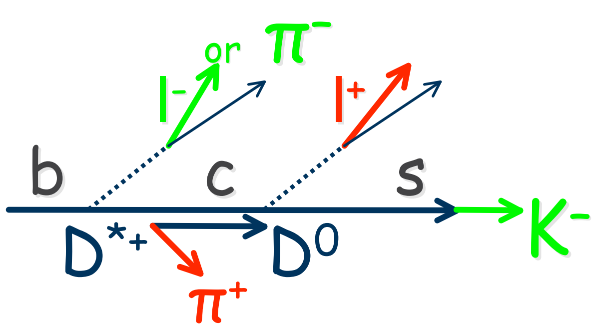
M_{bc} (Beam-constrained mass)

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



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*+->D⁰π⁺}

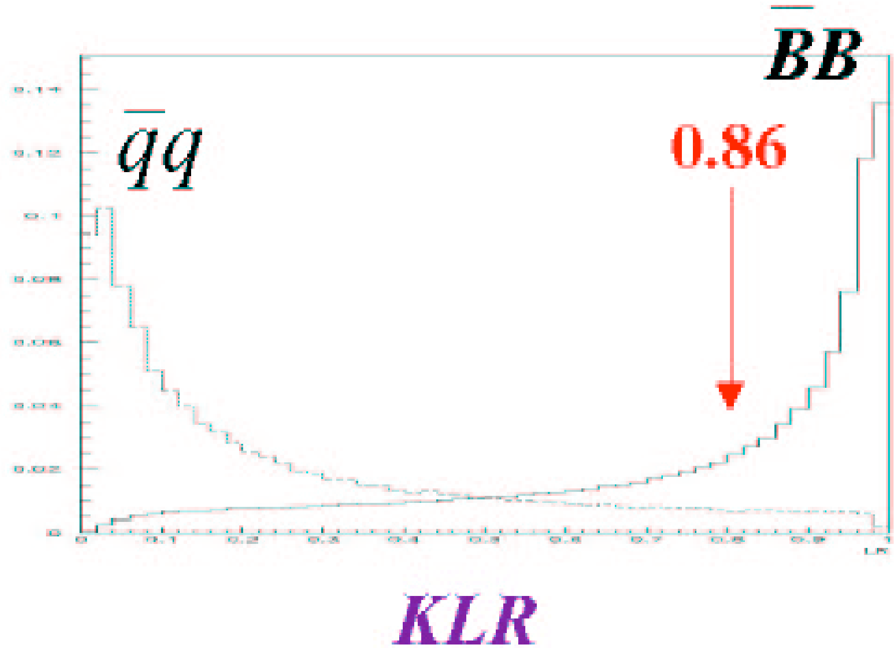
hard π b->{c}π⁻X

- multidimensional likelihood, ε>99%
- incorrect tag reduces ε, net (28.7±0.5)%

time-dependent CP analysis: overview

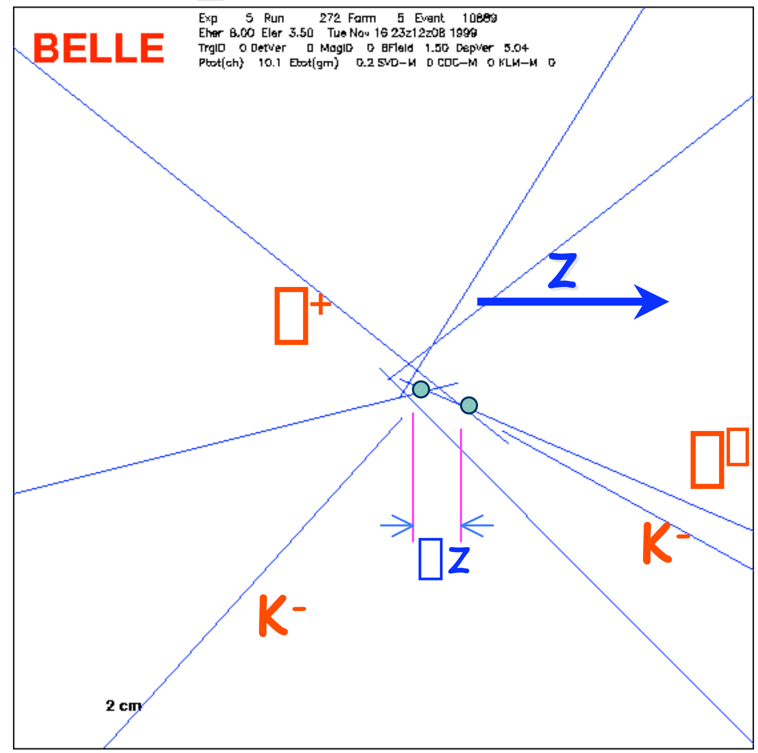
3) Continuum suppression

event parameterss, likelihood ratio



4) Vertex reconstruction

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



5) Fit to Δt distribution:

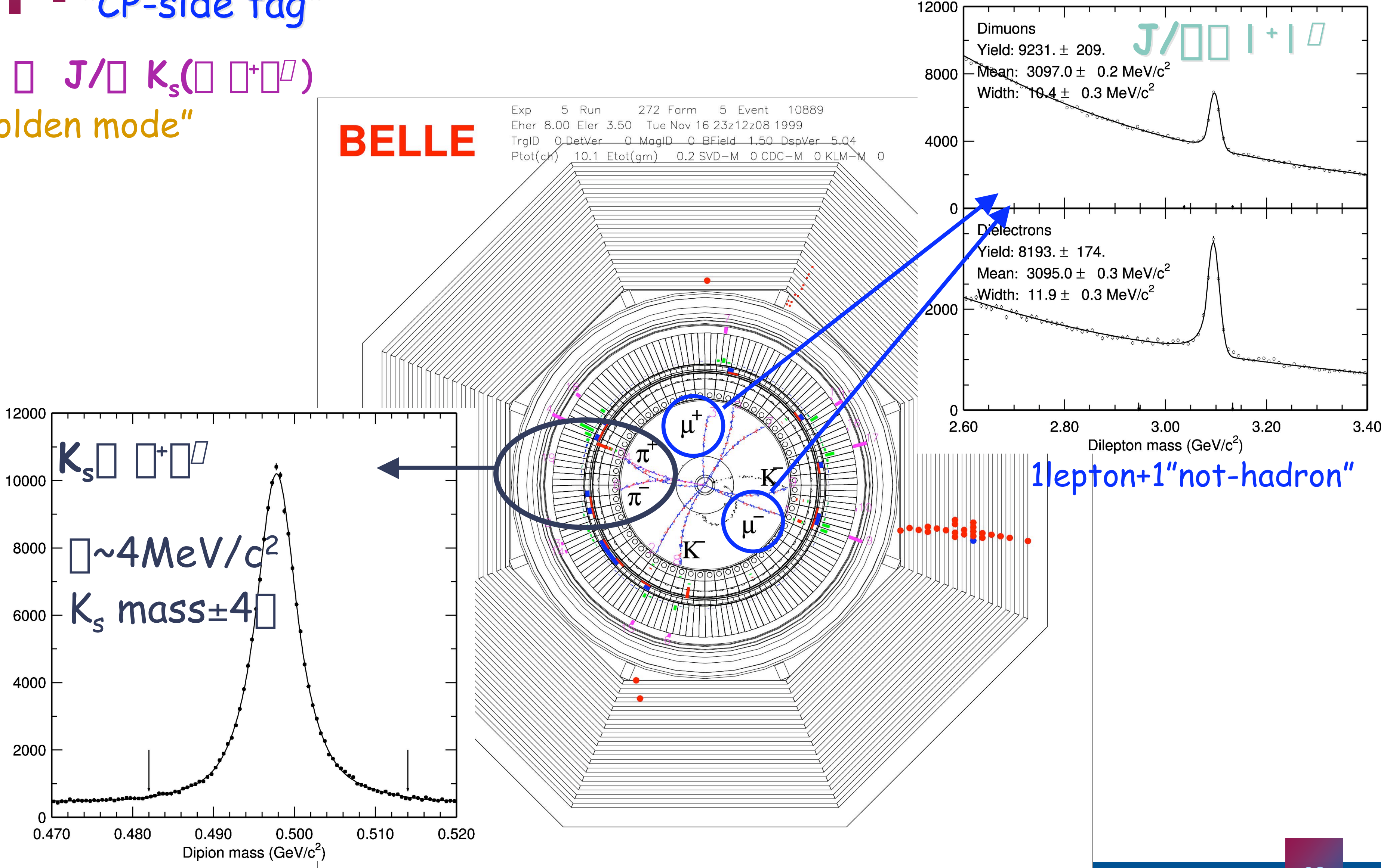
unbinned maximum likelihood

e.g., for $\sin 2\phi_1$ - reconstruct CP eigenstate decays

"CP-side tag"

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

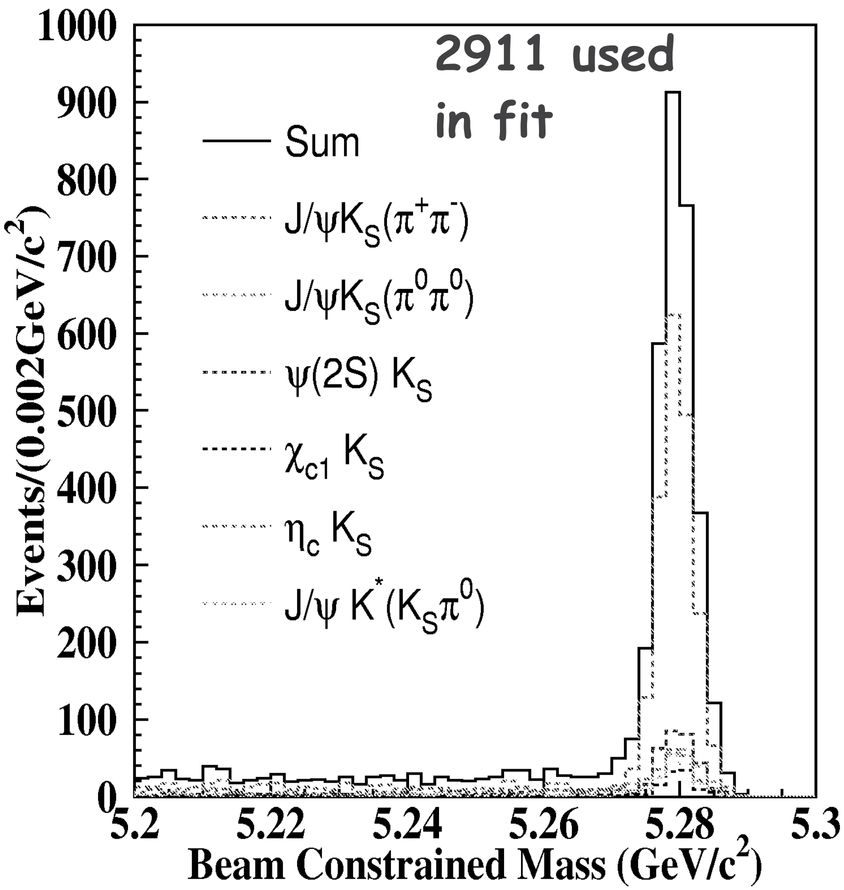
"golden mode"



sin2□$_1$: {charmonium}+K_s tag (CP=-1)

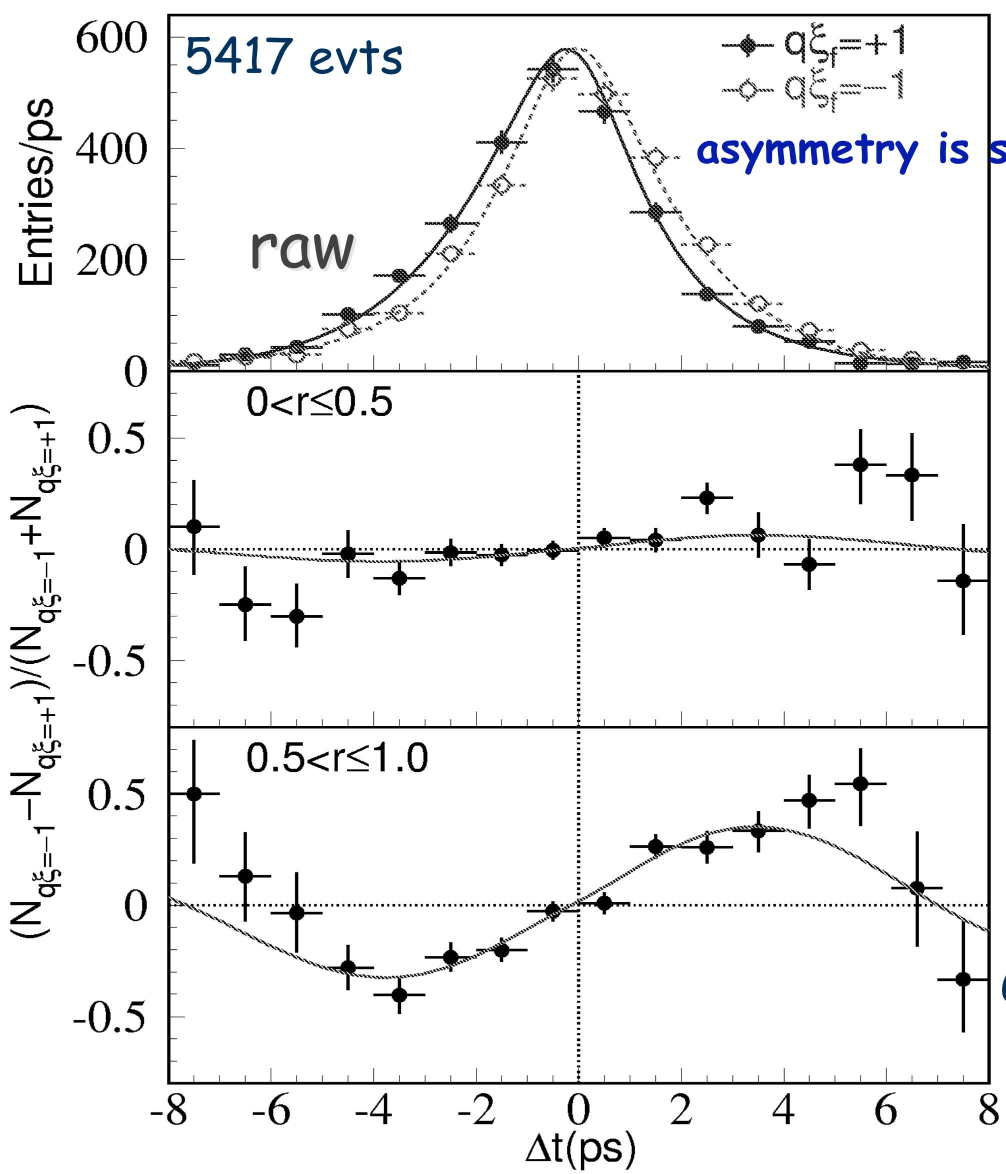
BELLE-CONF-0353

Fully reconstructed



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

Measurement of sin2ϕ_1



142 fb^{-1}

Poor tags

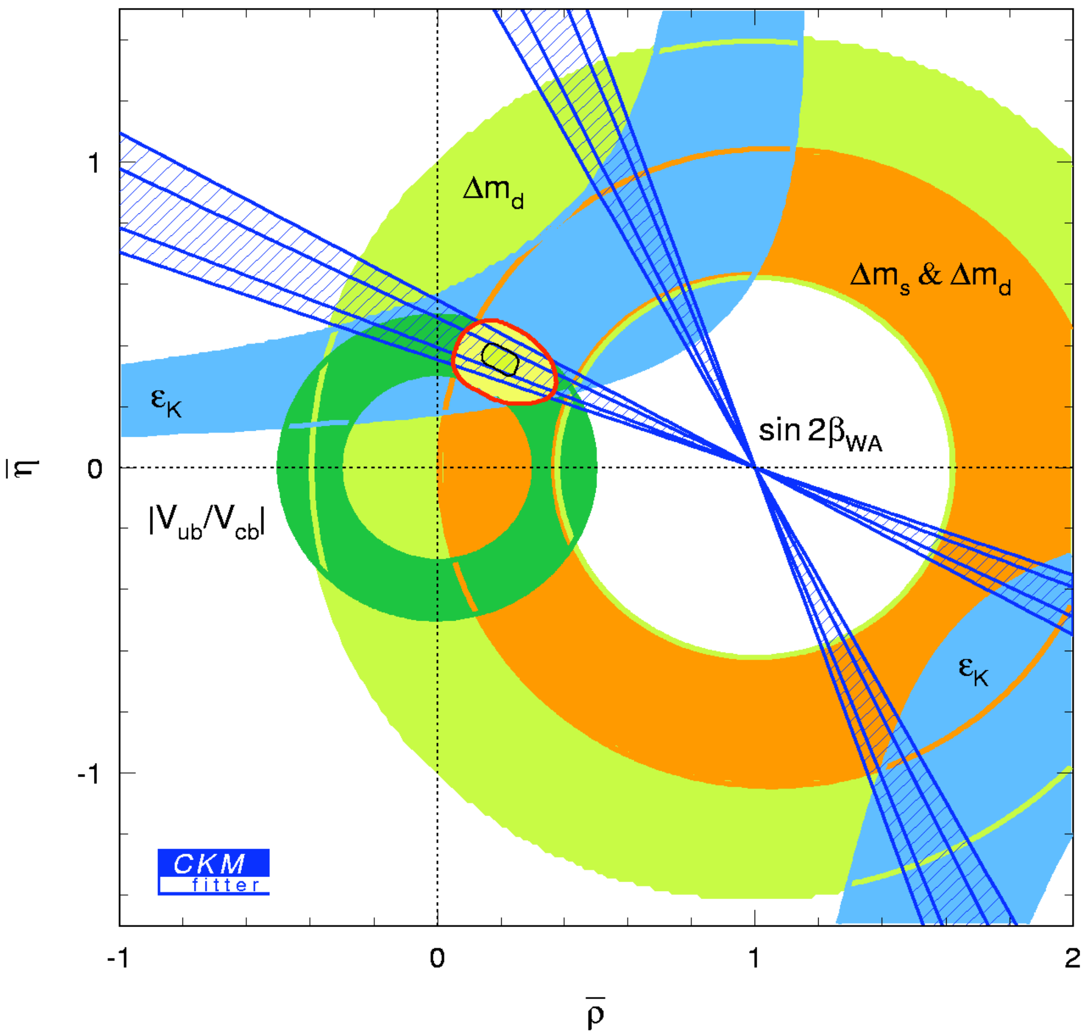
sin2ϕ_1= 0.733±0.057±0.028

consistent with no direct CP violation

Good tags

BELLE-CONF-0353

world average from {cc}K



$\sin 2\phi_1$ (Belle 2003, 140 fb^{-1})
=0.733±0.057±0.028

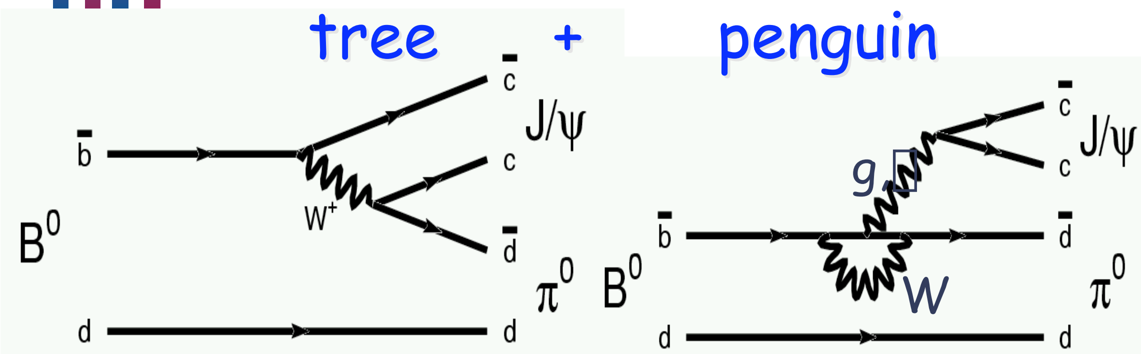
$\sin 2\phi_1$ (BaBar 2002, 81 fb^{-1})
=0.741±0.067±0.033

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

=0.736±0.049

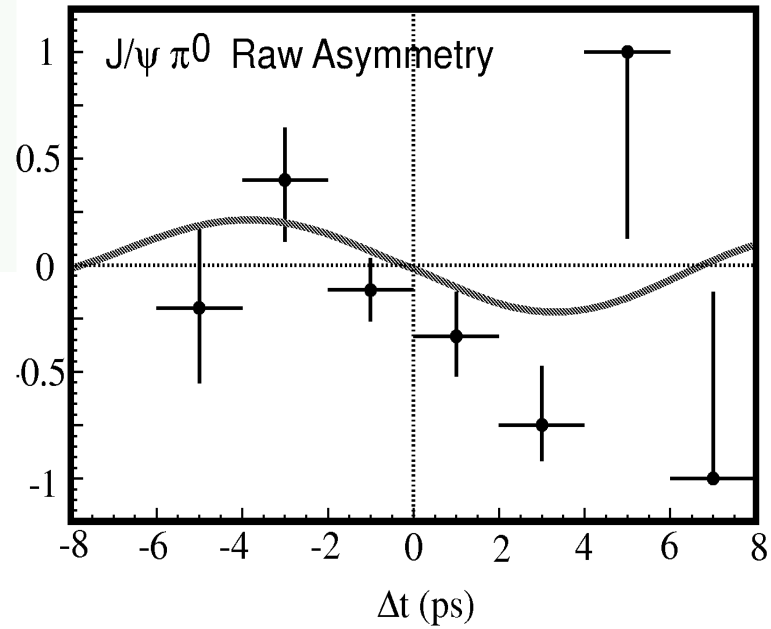
b->{c $\bar{c}$ d} decays: B->J/ψ π^0 (CP=+1)

tree + penguin

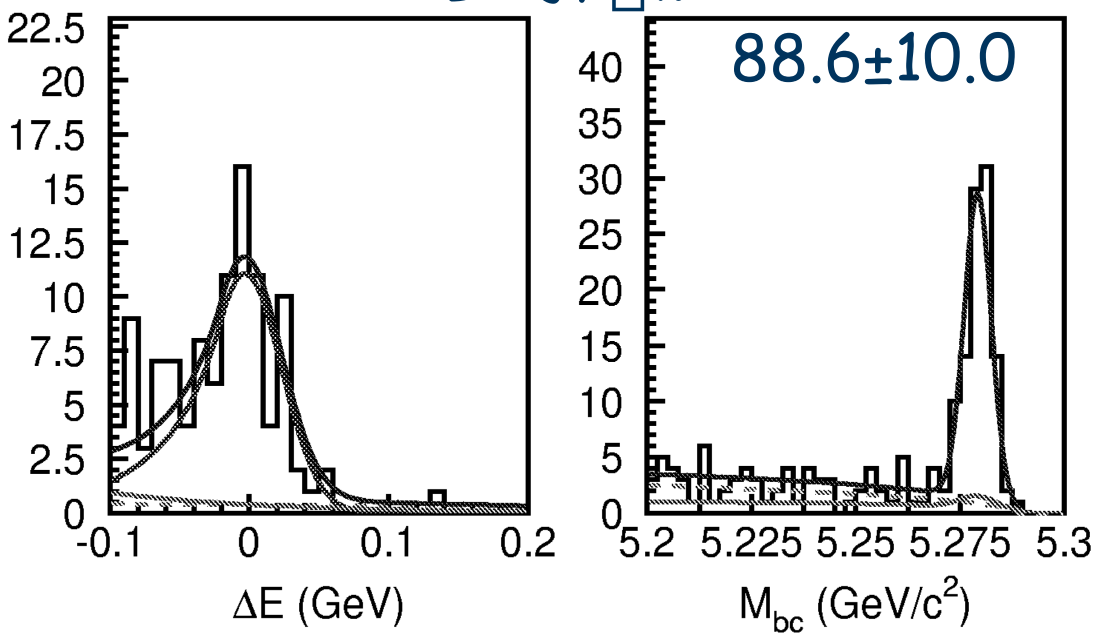


(relative amplitudes, strong phase not known)

expect S = -sin2ϕ_1 if penguin is small



B->J/ψ π^0



S = -0.72±0.42±0.08

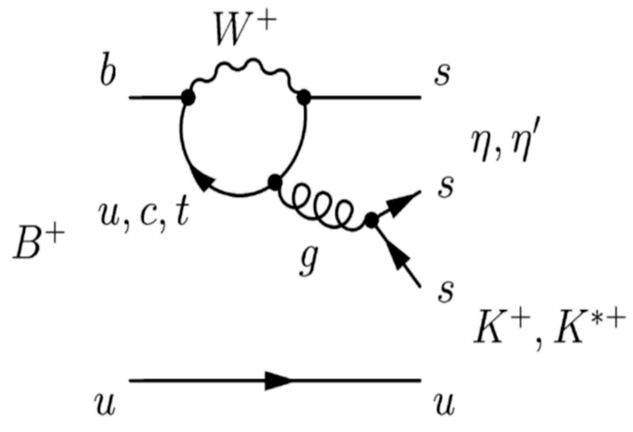
A = -0.01±0.29±0.07

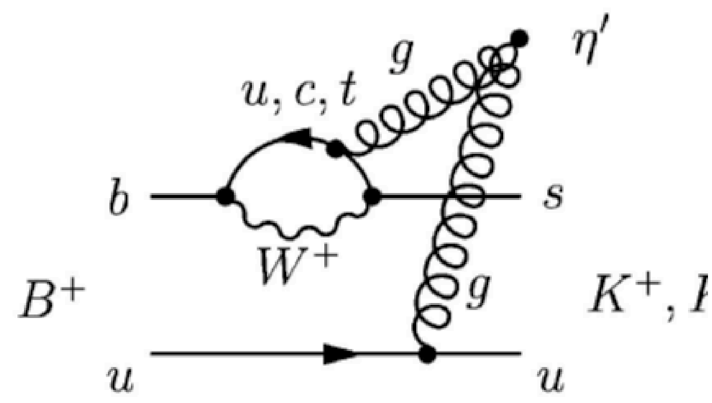
sin2ϕ_1 (World Av.)=0.736±0.049

BELLE-CONF-0342+

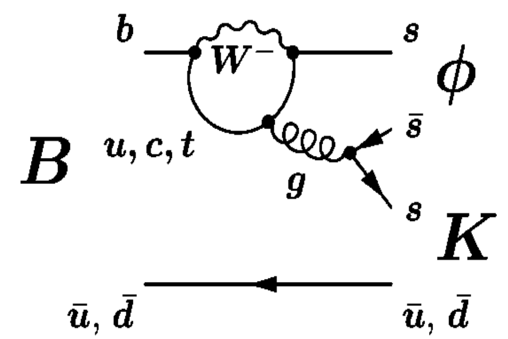
More time-dependent sin2□$_1$ – or new physics?

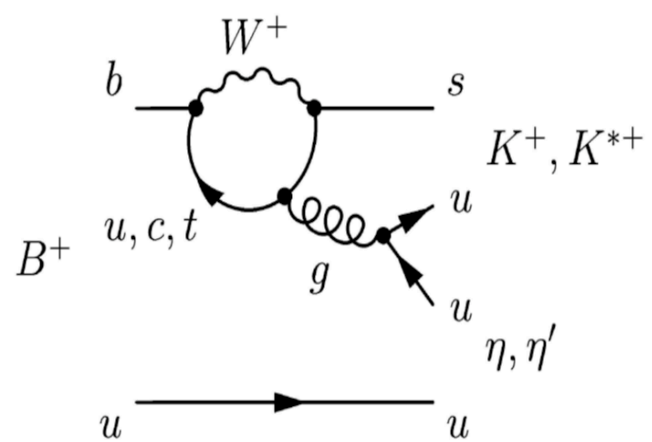
modes dominated by b->s$q\bar{q}$ penguins

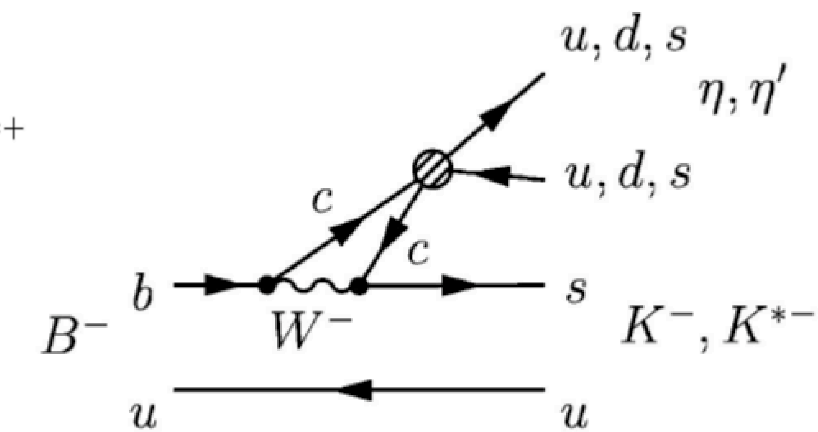




Theoretically cleanest



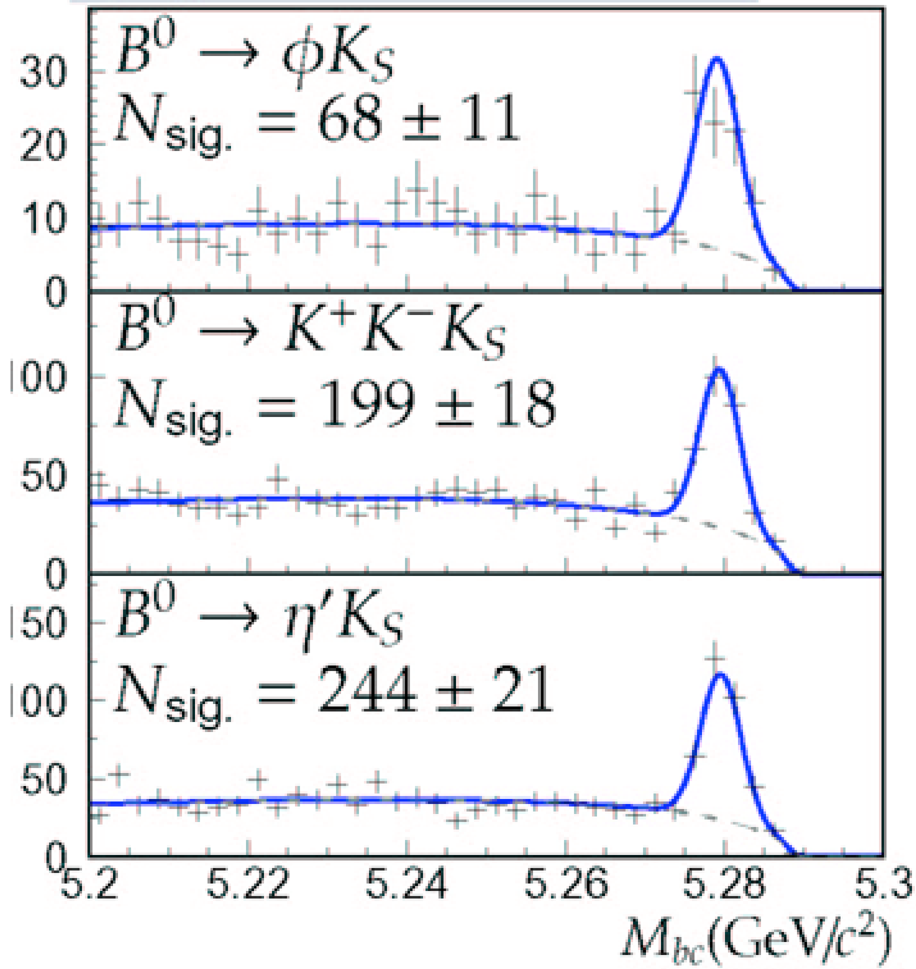




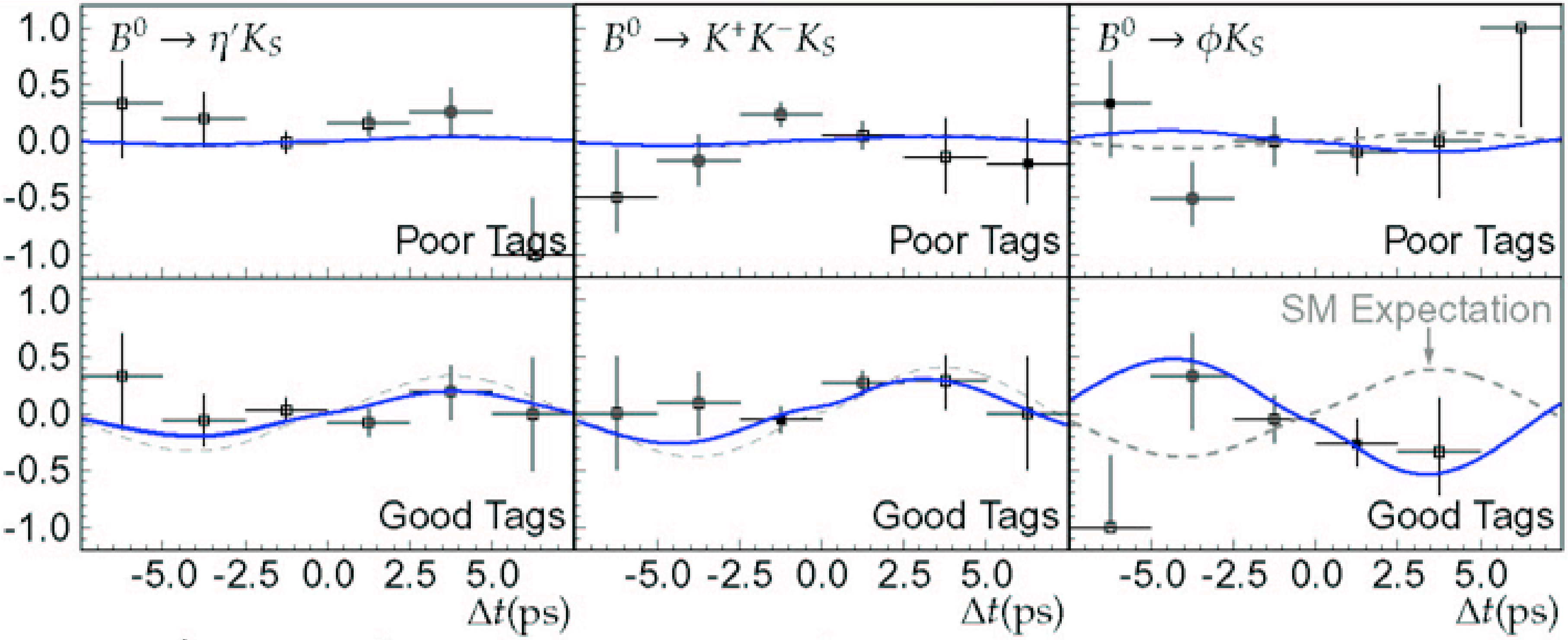
in the absence of New Physics, S = sin2□$_1$

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



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.

differs by 3.5σ

PRL 91, 261602 (2003)

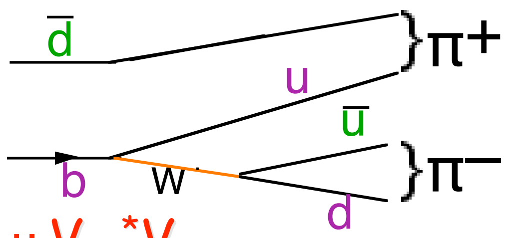
[sin2ϕ_1(world average) = 0.736±0.049]

sin2$\square_2$: $B^0 \to \pi^+\pi^-$

$\square_2 = \arg \frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}$

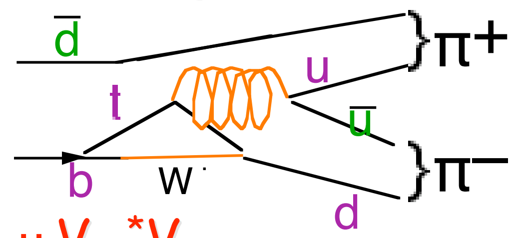
2 paths, each w/wo mixing:

Tree (T)

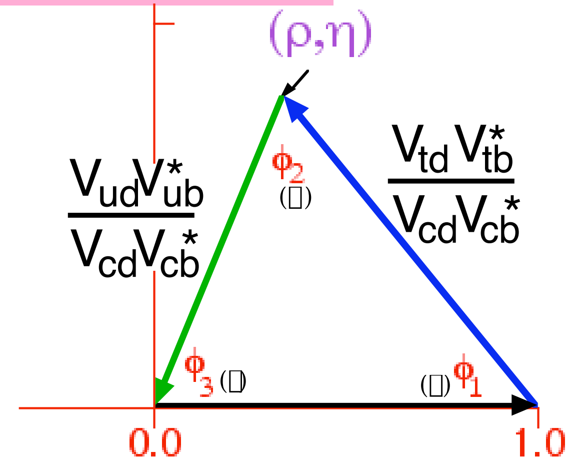


$\mu\, V_{ub}^* V_{ud}$

Penguin



$\mu\, V_{tb}^* V_{td}$



mixing+ "

$\mu\, V_{tb}^{*2} V_{td}^2 V_{ub} V_{ud}^*$

mixing+ "

$\mu\, V_{tb}^{*2} V_{td}^2 V_{tb} V_{td}^*$

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, $A_{\pi\pi}=0$, $S_{\pi\pi}=\sin 2\square_2$
- if P, T comparable, $A_{\pi\pi}\neq 0$, $S_{\pi\pi}\sim\sin(2\square_2+2\square)\cdot 2/(|\square|^2+1)$

difference of strong phase

≠1 if direct CP violation

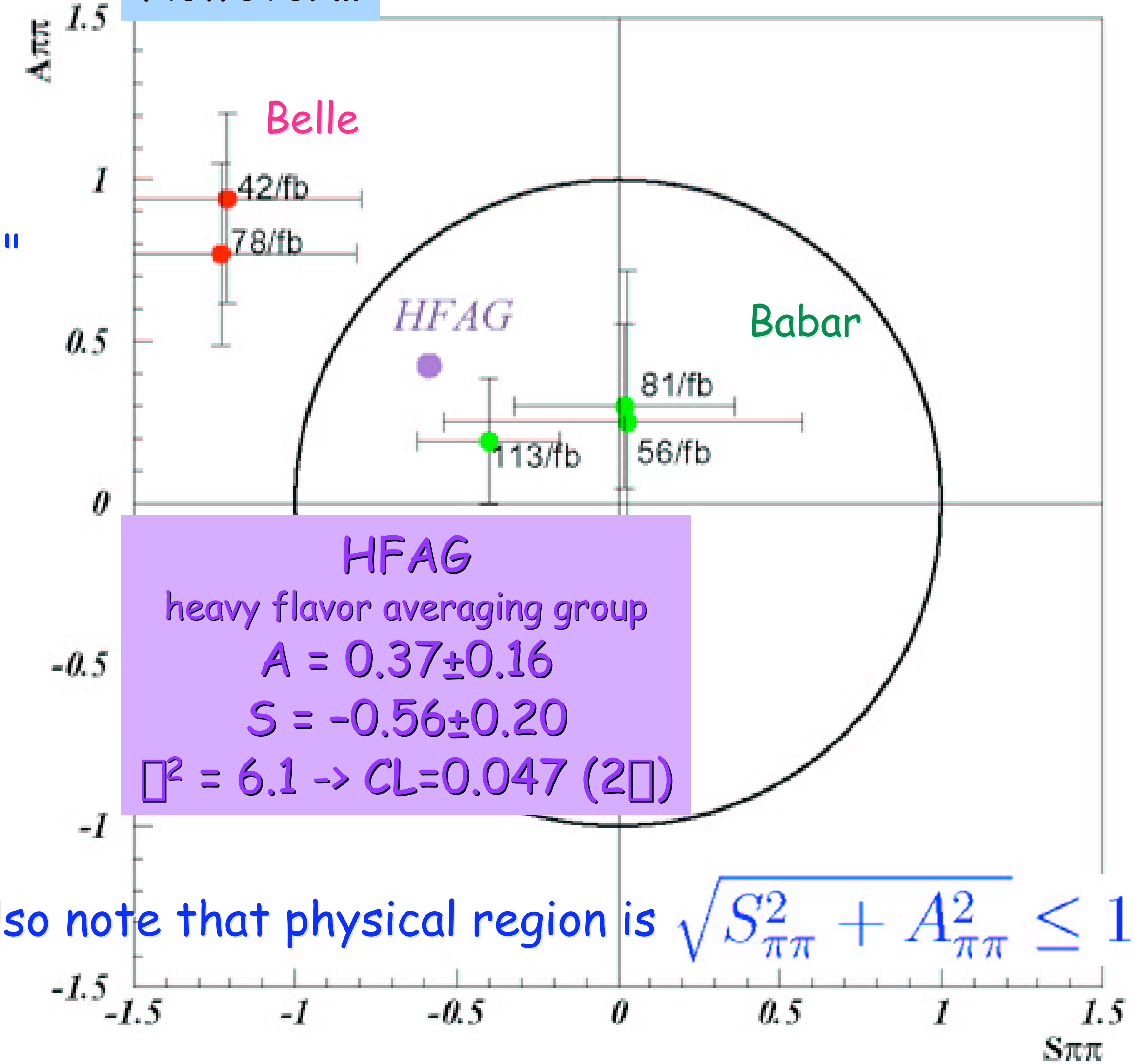
history

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
$A = 0.37 \pm 0.16$
$S = -0.56 \pm 0.20$
$\chi^2 = 6.1 \to CL=0.047\ (2\sigma)$

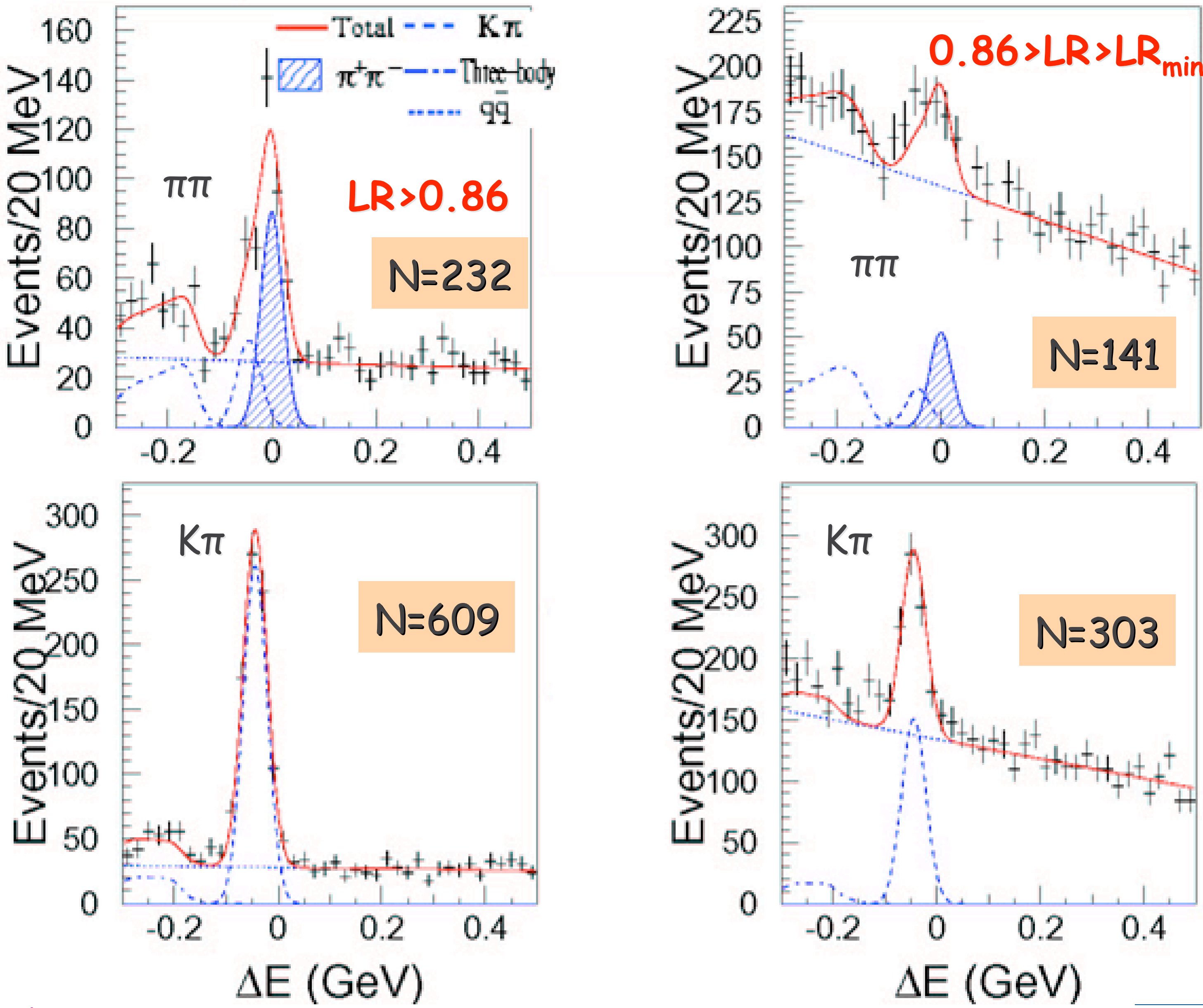
… also note that physical region is $\sqrt{S_{\pi\pi}^2 + A_{\pi\pi}^2} \leq 1$

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

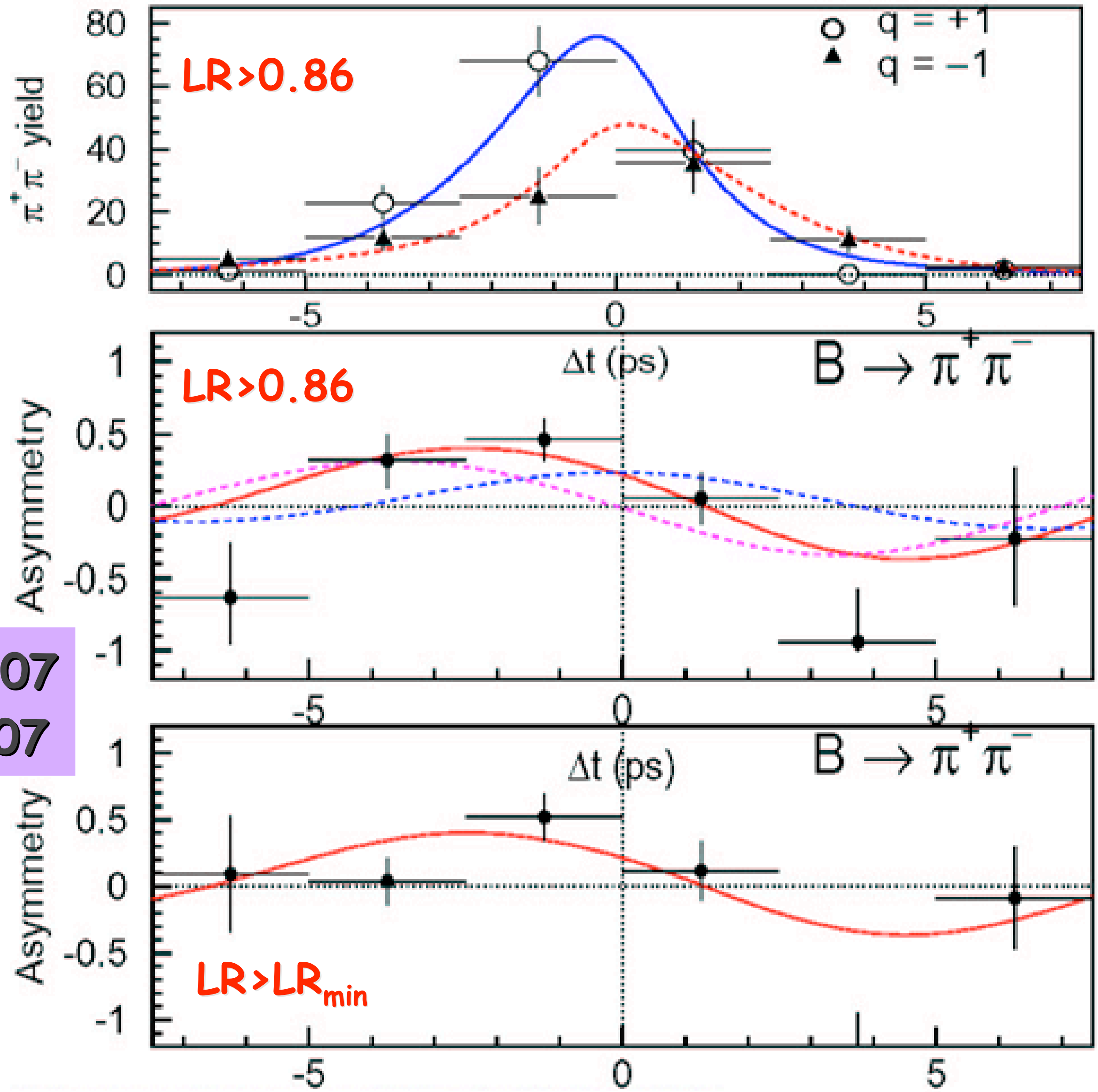
… less clean than $B^0 \to J/$□K_s:

- "physics bkg" $B^0 \to K^+\pi^-$ => hadron ID, kinematics
  - dE/dx, TOF, Aerogel – "positive ID" □$_\pi$=91%, □$_k$=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:
    - $LR > 0.86$ {□$_{BB}$=53%, □$_{qq}$=5%}
    - $0.86 > LR > LR_{min}$ (cut depends on flavor tag classification)

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



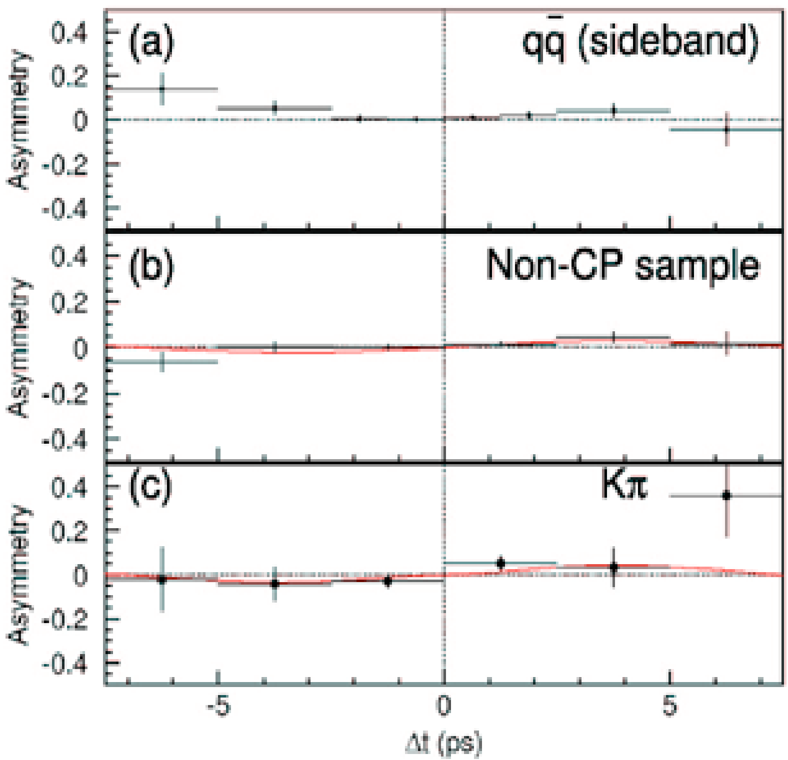
Result of fit



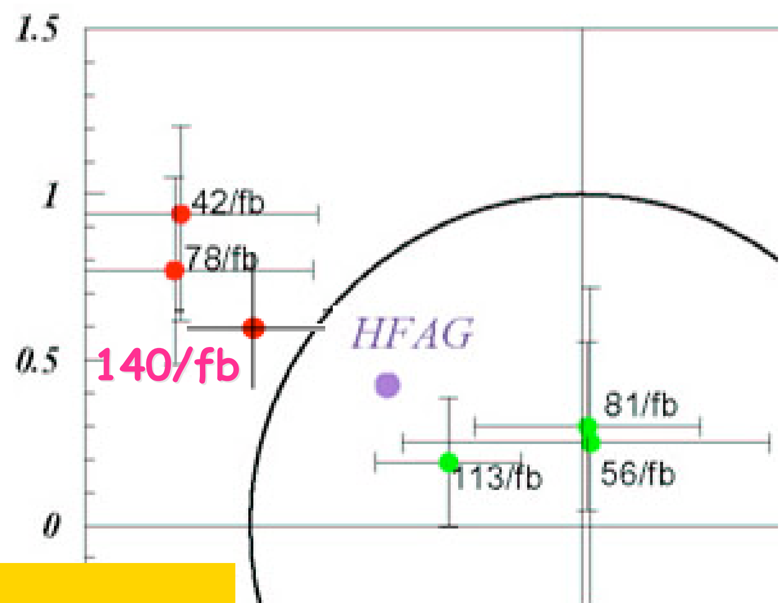
A = +0.58±0.15±0.07
S = −1.00±0.21±0.07

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



Conclusion

Observation of CP violation (5.2σ)

Evidence for direct CP violation (3.2σ)

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

Summary

Belle in 2004:

- KEKB *luminosity* $1.20 \times 10^{34} cm^{-2}s^{-1}$ (design: 1×10^{34}); >220 B pairs
- $\sin 2\phi_1$ is now a "precision" measurement
- first results on alternative probes of $\sin 2\phi_1$ (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!