



Reflections on Beauty:



CP Asymmetries in B Meson Decay

- Weak interactions & the b-quark: CKM matrix
- B(eauty) mesons & CP
- B meson production: $e^+e^- \rightarrow \Upsilon(4S)$
- Belle/Babar experiment

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Symmetry of Physical Laws

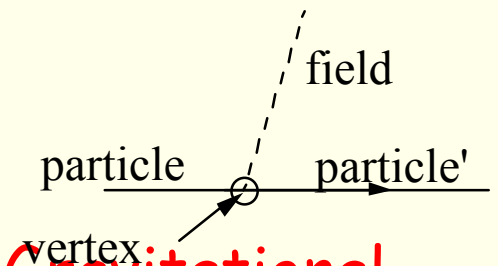
In interaction-free universe (4-d, relativistic QM)

- massless particles
- symmetric in transformations

$P(r \leftrightarrow -r)$, $C(\text{particle} \leftrightarrow \text{antiparticle})$, $T(t \leftrightarrow -t)$

Add interactions: emission/absorption of field quantum

- mass via self-interaction
- interaction strength/probability
 \propto "charge" $g^2 \propto$ "coupling constant"
- symmetry info in vertex



Forces: Strong, Electromagnetic, Weak, Gravitational

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



Weak Interaction

The only force known to

- allow particle to change identity
- violate P symmetry (maximally)
right-handed particles, left-handed antiparticles.
no coupling to LH particles, RH antiparticles.
- violate CP symmetry (a little)

Why is CP violation of interest?

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

What is source of observed CP asymmetry?



We have an interesting possibility ...

Standard Model = 12 fermion flavors (+antifermion)

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

distinguished ONLY by mass (?)

fermions: 3 generations \times 2 types \times 2 ea (doublets)
all stable, if not for weak interaction

		Generation		
type	Q/ e	1	2	3
lepton (no strong)	-1	e electron	μ muon	τ tau
	0	ν_e neutrino	ν_μ neutrino	ν_τ neutrino
quark (strong)	+2/3	Up	Charm	Truth
	-1/3	down	Strange	beauty



Weak couplings

Z^0

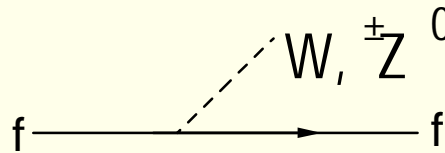
"neutral current"

$$\Delta Q = 0$$

$$l^\pm \leftrightarrow l^\pm$$

$$q^{+2/3} \leftrightarrow q'^{+2/3}$$

NO generation x-ing
 → no flavor-changing
 single coupling strength



W^\pm

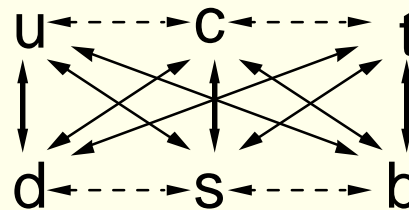
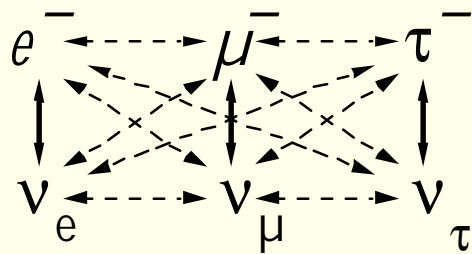
"charged current"

$$\Delta Q = \pm 1$$

$$l^- \leftrightarrow \nu$$

$$q^{+2/3} \leftrightarrow q'^{-1/3}$$

(small) generation x-ing,
 quark only
 all different strengths



↔ seen

↔ suppressed

--- not seen

Large # of fundamental "charges" – can this be simplified?



GIM mechanism

Explains

- suppression of flavor-changing neutral currents
- multiplicity of charged current couplings
- for >2 generations, **CP violation**

Picture

- strong doublets, “degenerate” generations, 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:

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

Cabibbo-Kobayashi-Maskawa (CKM) matrix

complex
preserves metric
“orthogonality” } = **unitary**

For 3 x 3, unitarity constrains {9 real+9 imaginary} dof to 4 free parameters, incl. **1 irreducible imaginary part**



Unitarity of CKM

(Wolfenstein parametrization):

$$1/g_F \times W\text{-couplings: } \begin{matrix} & d & s & b \\ \begin{matrix} u \\ c \\ t \end{matrix} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{matrix} \cong \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

Unitarity condition:

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

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

$$\begin{matrix} \downarrow & & \downarrow \\ -(\rho+i\eta) & & -(1-\rho-i\eta) \end{matrix}$$

(ρ, η) : "unitarity triangle"

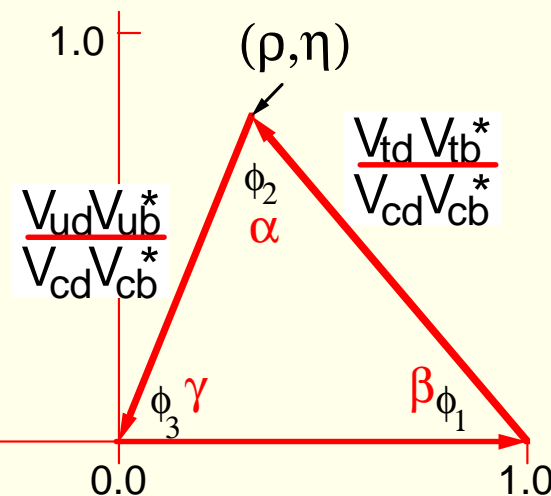
from decay rates,

$$\lambda = 0.220 \pm 0.002$$

$$A = 0.81 \pm 0.08$$

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

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



Self-consistent if CKM is correct



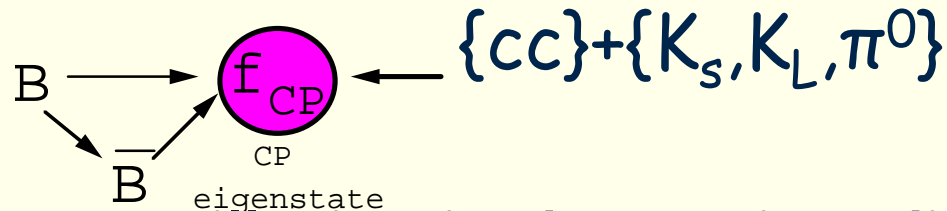
Complex couplings revealed via CP asymmetry

- t-integrated rates $\Gamma \propto |\langle f | H_{int} | i \rangle|^2 \Rightarrow$ not sensitive to phase:

$$CP\left\{ \begin{array}{c} \text{---} \nearrow V_{xy} \text{---} \\ \text{x} \xrightarrow{\quad} \text{y} \end{array} \right\} = \begin{array}{c} \text{---} \nearrow V_{xy}^* \text{---} \\ \bar{\text{x}} \xrightarrow{\quad} \bar{\text{y}} \end{array}$$

- need interference between processes:

e.g., decays to CP eigenstate - paths w/wo mixing interfere

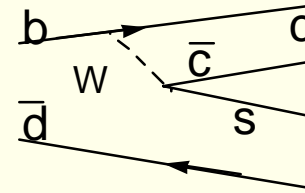
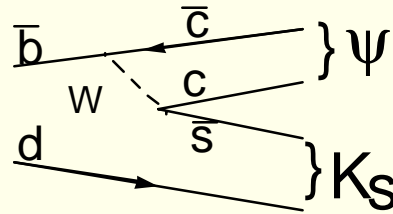


-> CP-dependent oscillation in decay time distributions

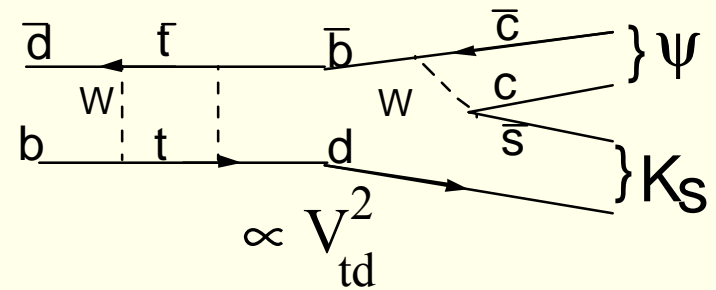
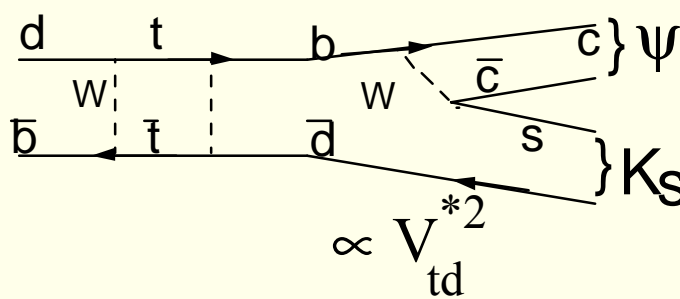


CP Asymmetry of $B \rightarrow J/\psi K_S$

tree (real V_{ij})



mixing+tree



$$\arg(V_{td}^2) = 2\phi_1$$

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

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

* No theoretical uncertainty

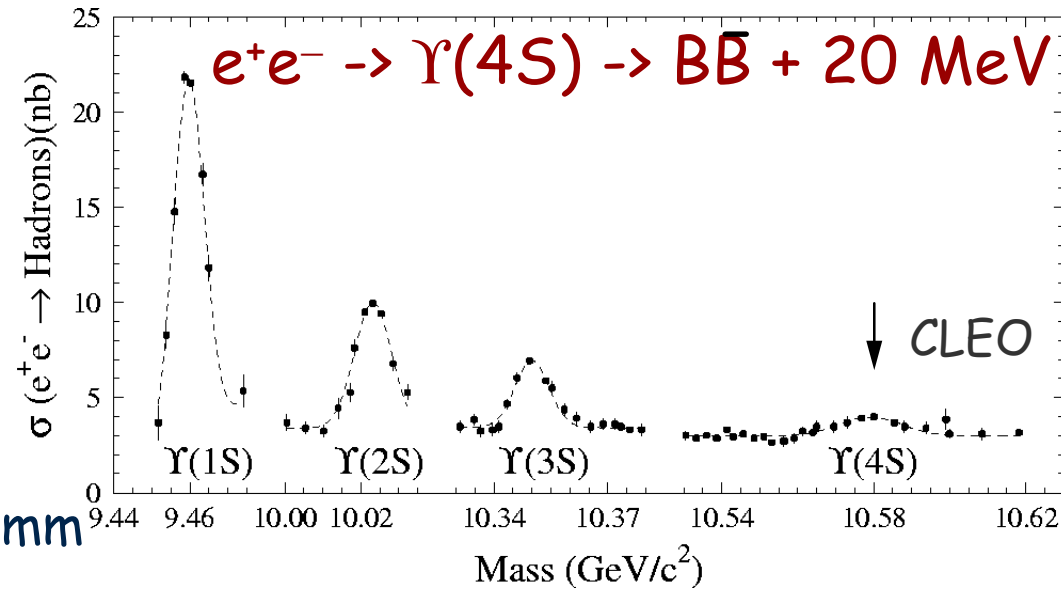
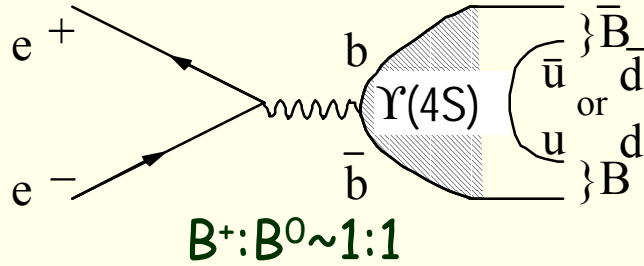


Measure time dependence - what's needed?

- B pair production $\Rightarrow e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$
- Measure decay-time difference
 - Asymmetric energy $e^+e^- \Rightarrow$ (@KEKB: $\gamma\beta c\tau \approx 200\mu\text{m}$)
 - good vertexing \Rightarrow silicon strip vertex detector
- Find CP eigenstate decays
 - high quality $\sim 4\pi$ detector \Rightarrow Belle/Babar
- Tag other B's flavor
 - good hadron id $\Rightarrow dE/dx, \text{Aerogel}, \text{TOF}, \text{DIRC}$
 - good lepton id $\Rightarrow \text{CsI}, \text{multilayer } \mu$
- Lots of B mesons $\sim 10^8$ ($Br(B \rightarrow f_{CP}) \sim 10^{-3}$)
 - very high Luminosity \Rightarrow KEKB/PEP2



BB pair production: Upsilon



KEKB:

8.0 GeV e^- + 3.5 GeV e^+
 IP size = $77 \mu\text{m} \times 2.0 \mu\text{m} \times 4.0 \text{mm}$

Event rate

Cross section $\sim 1 \text{ nb} = 10^{-33} \text{ cm}^2$

$$\frac{dN}{dt} = \sigma \times L \leftarrow \text{Luminosity (collision rate)}$$

$\sim 10 \text{ s}^{-1}$ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (design; currently 5.5×10^{33} @KEKB)

$\sim 10^8 \text{ yr}^{-1}$

Currently@Belle: 3×10^7 BB \bar{e} events (published), 4.8×10^7 on tape

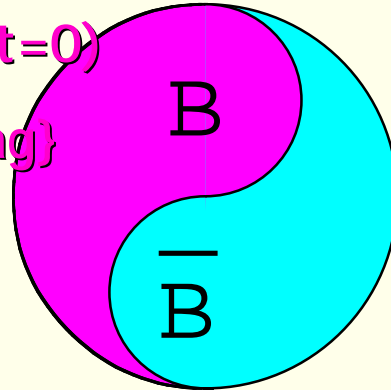


Time measurement at $\Upsilon(4S)$

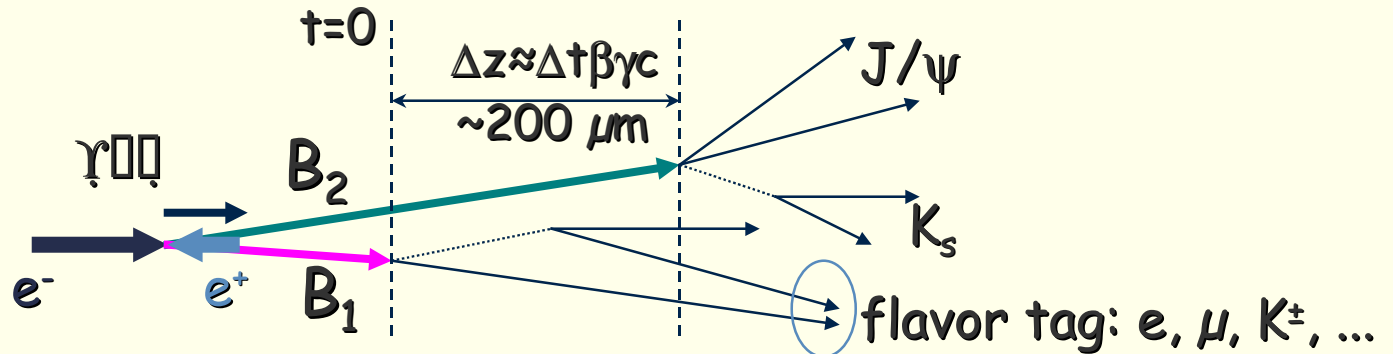
$\Upsilon(4S)$: $CP=-1$, conserved

until first B decay ($t=0$)

identify b/\bar{b} {flavor tag}



Reconstruct $CP=\pm 1$ mode @ $t=\Delta t$





Detector: e.g. Belle

Designed to measure *CP* asymmetry

Charged tracking/vertexing

- SVD: 3-layer DSSD Si μ strip ($\sim 55 \mu\text{m}$)
- CDC: 50 layers (He-ethane)

Hadron identification

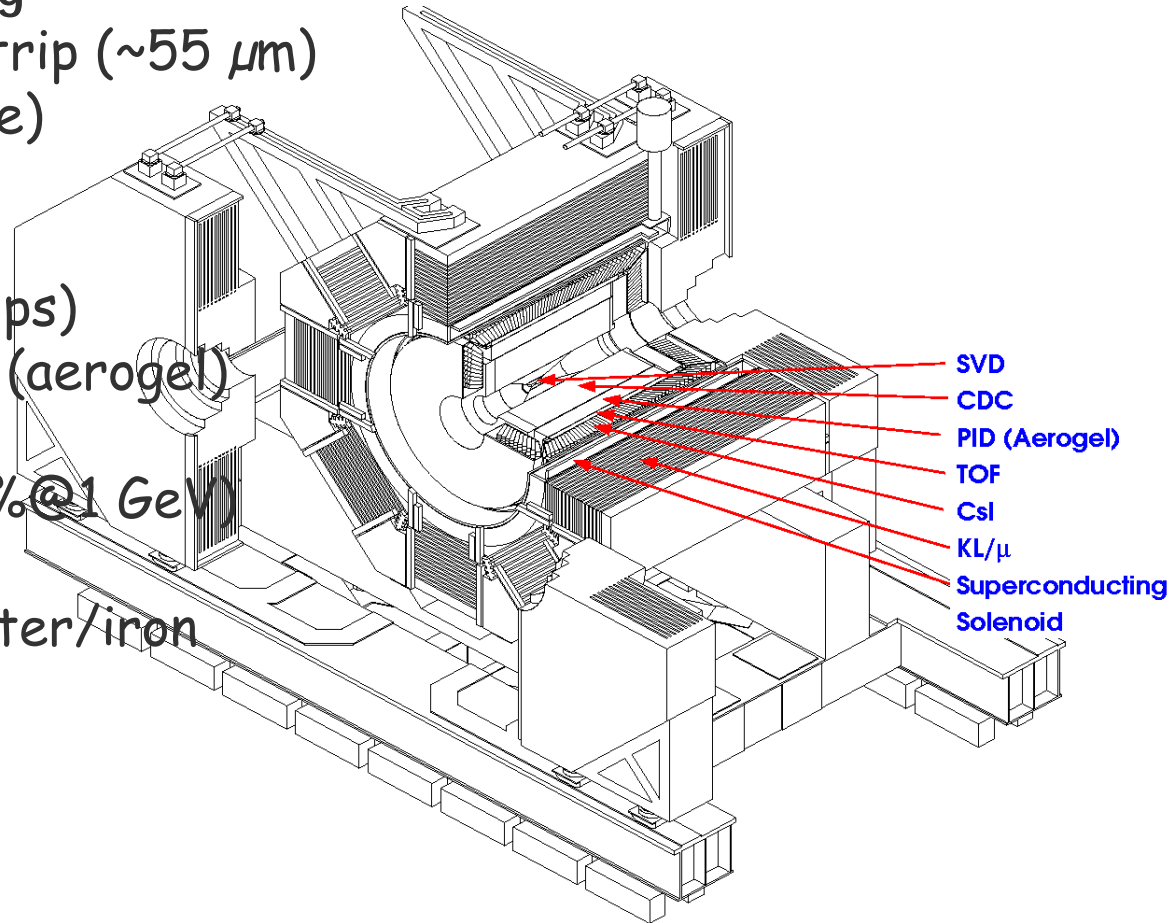
- CDC: dE/dx ($\sim 7\%$)
- TOF: time-of-flight ($\sim 95 \text{ ps}$)
- ACC: Threshold Cerenkov (aerogel)

Electron/photon

- ECL: CsI calorimeter (1.5% @ 1 GeV)

Muon/KL

- KLM: Resistive plate counter/iron





Belle Collaboration

VOLUME 86, NUMBER 12

PHYSICAL REVIEW LETTERS

19 MARCH 2001

VOLUME 86, NUMBER 12

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19 MARCH 2001

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

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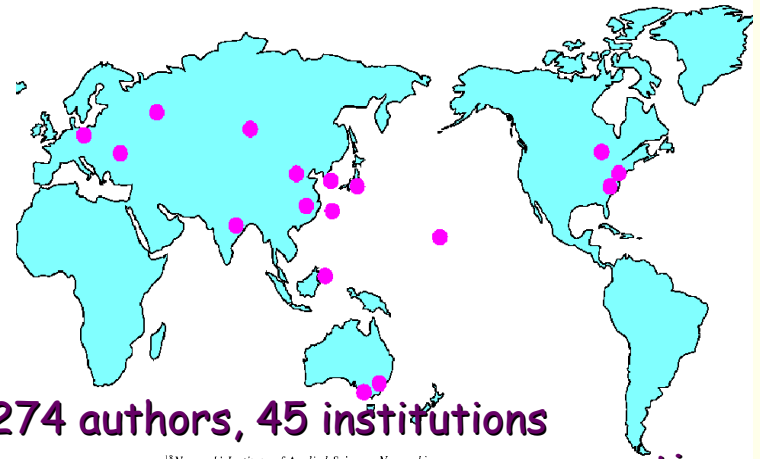
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(Received 9 February 2001)

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 $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\chi_{c0}K_S$, $J/\psi K_L$, 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 $\sin 2\phi_1 = 0.58^{+0.22}_{-0.19}(\text{stat})^{+0.08}_{-0.08}(\text{sys})$.

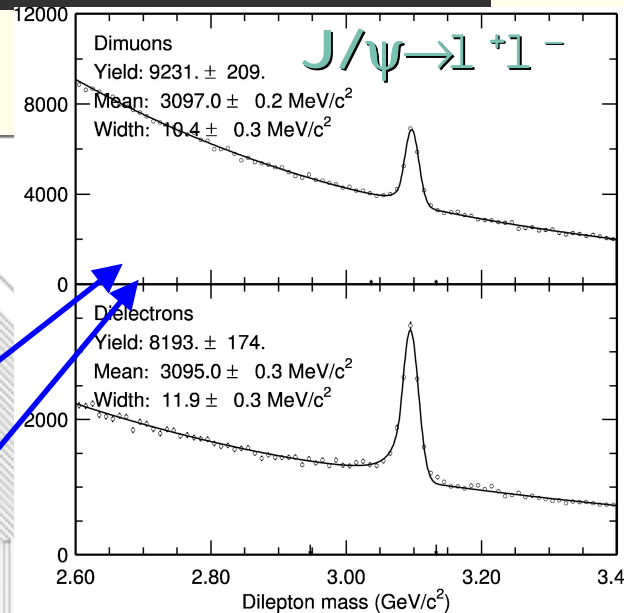
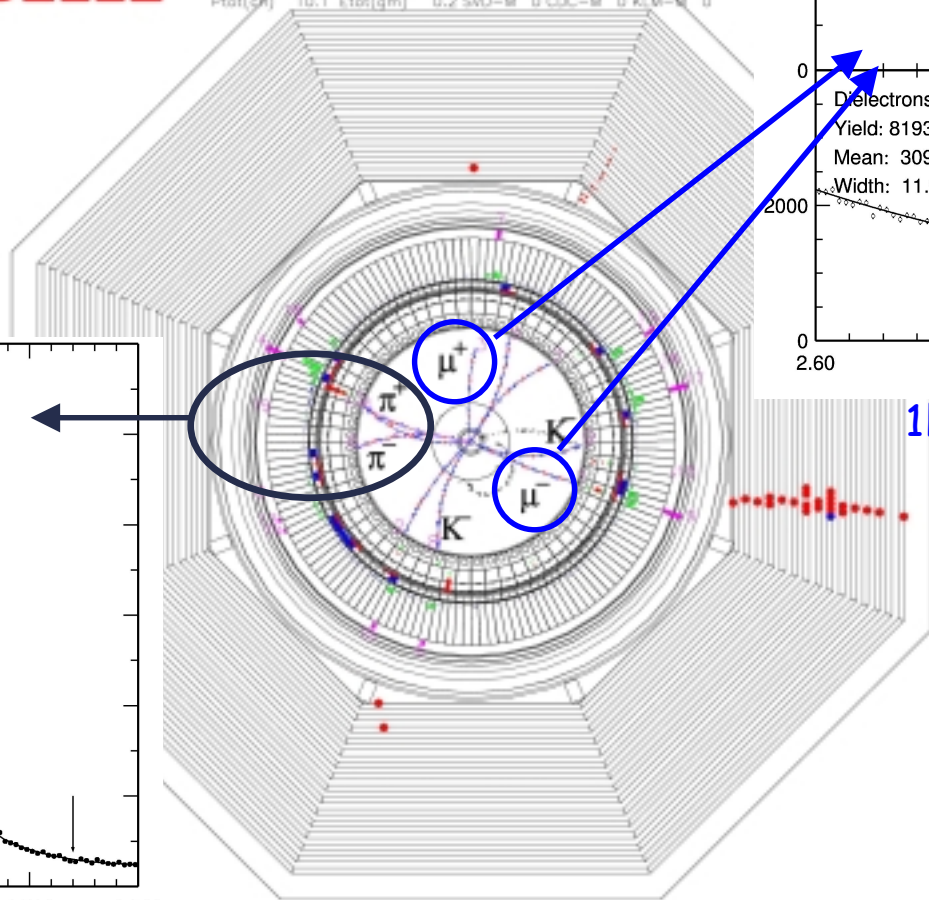


CP mode reconstruction

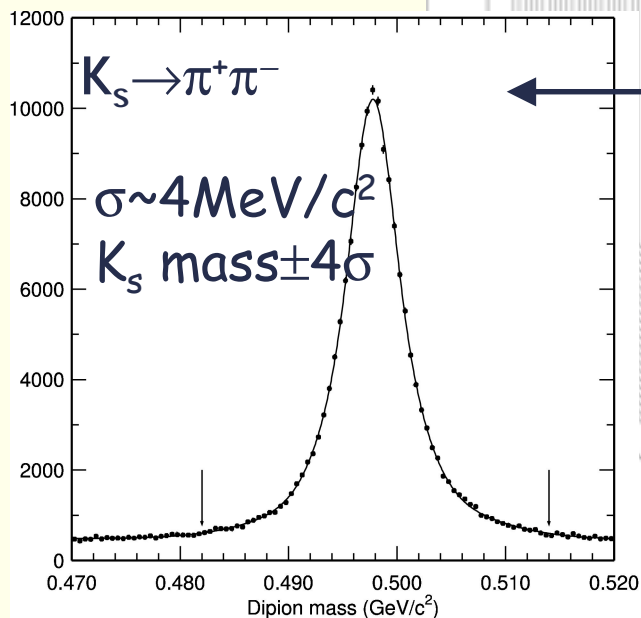
$B^0 \rightarrow J/\psi K_S (\rightarrow \pi^+ \pi^-)$
"golden mode"

BELLE

Exp 5 Run 272 Farm 5 Event 10889
Eler 8.00 Eler 3.50 Tue Nov 16 23:12:08 1999
TrigID 0 DetVer 0 MagID 0 BField 1.50 DipVer 5.04
Plat(ch) 10.1 Etof(gm) 0.2 SVD-M 0 CDC-M 0 KLM-M 0



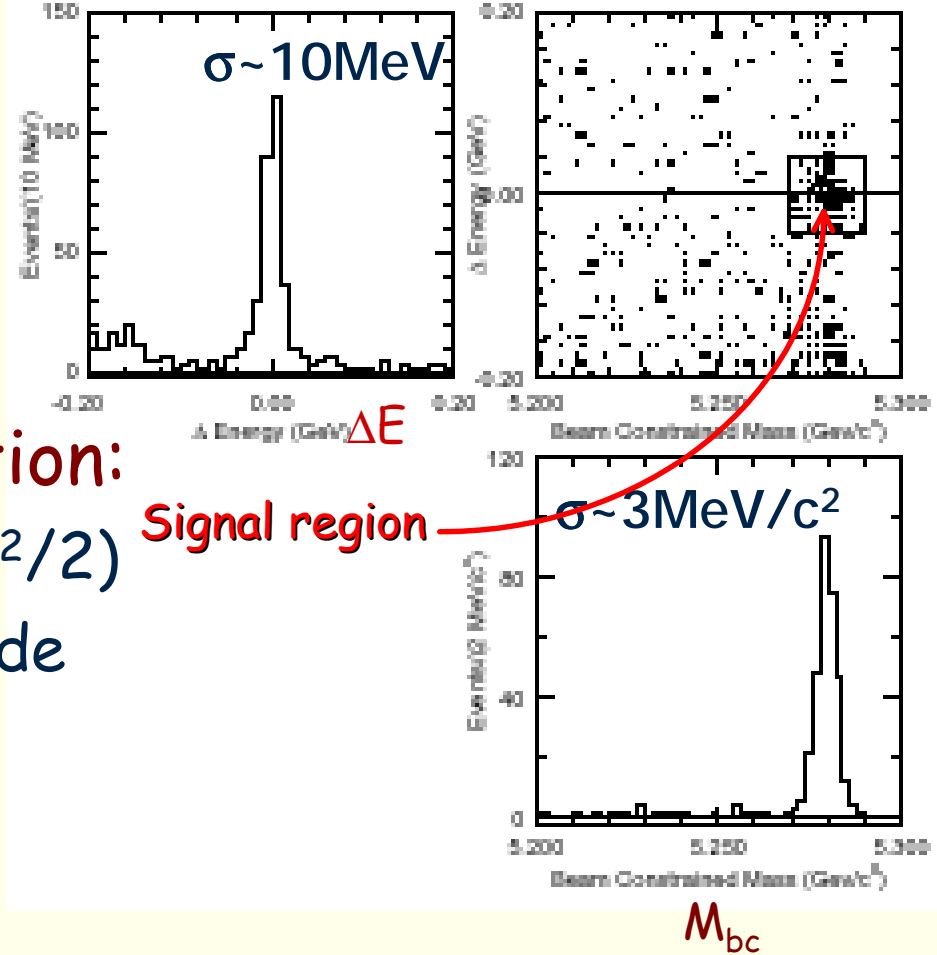
1lepton+1"not-hadron"





$B^0 \rightarrow J/\psi K_S$ (continued)

457 events
~3% background



Kinematics for final selection:

$$\Delta E = E_{\text{cand}}^* - E_{\text{beam}}^* \approx 0 \quad (E_{\text{beam}}^* \approx \sqrt{s}/2)$$

10-50 MeV res, depends on mode

M_{bc} (Beam-constrained mass)

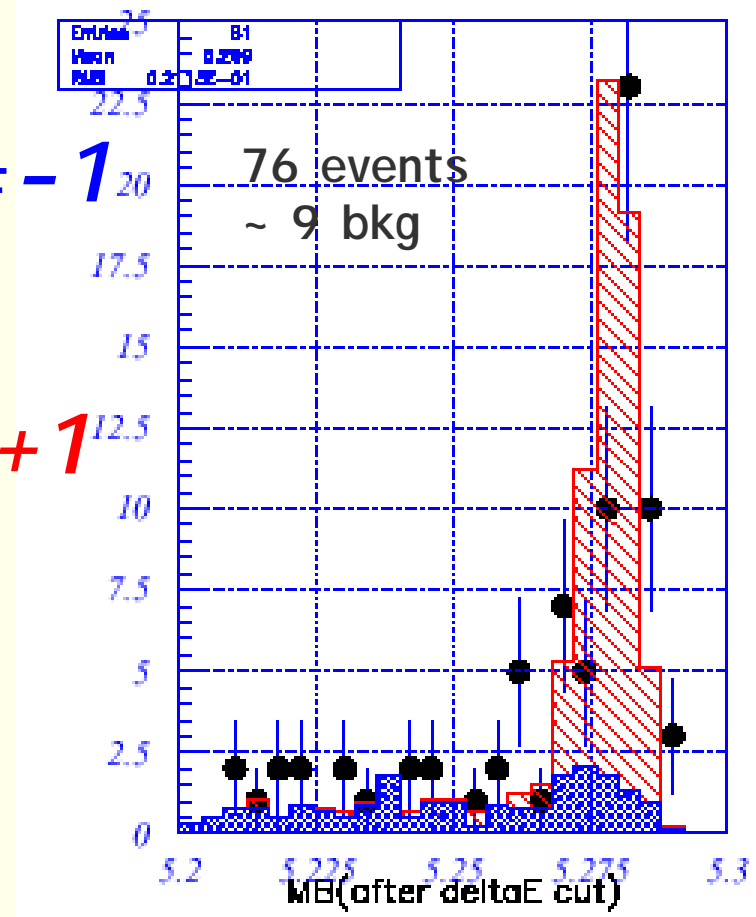
$$M_{bc} = (E_{\text{beam}}^{*2} - p_{\text{cand}}^{*2})^{1/2}$$



Other charmonium+K

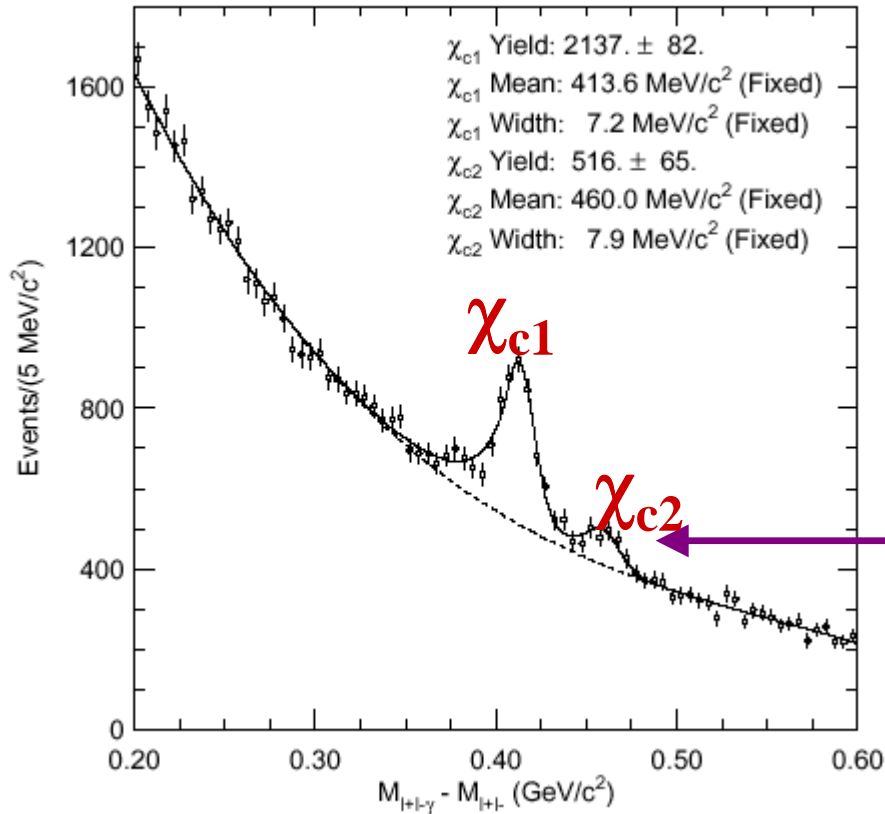


- $J/\psi K_S (\rightarrow \pi^+ \pi^- \text{ \& } \pi^0 \pi^0)$
 - $\psi(2S) (\rightarrow l^+ l^- \text{ \& } J/\psi \pi^+ \pi^-) K_S$
 - $\chi_{c1} (\rightarrow J/\psi \gamma) K_S$
 - $\eta_c (\rightarrow K_S K^+ \pi^-, K^+ K^- \pi^0) K_S$
 - $J/\psi K_L$
 - $J/\psi K^{*0} (\rightarrow K_L \pi^0) \text{ (mostly)}$
- $\left. \begin{array}{l} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \right\} \xi_f = -1$
 $\left. \begin{array}{l} \text{---} \\ \text{---} \end{array} \right\} \xi_f = +1$





Other charmonium



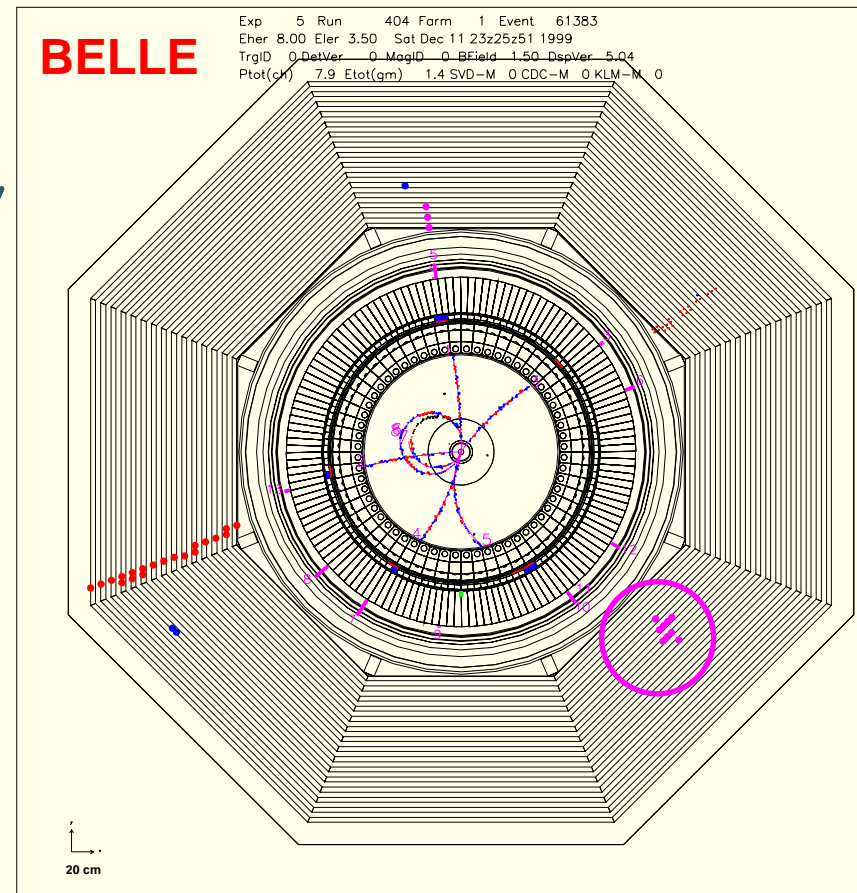
1st observation
of inclusive
 $B \rightarrow \chi_{c2} X$

$$M(l^+l^-\gamma) - M(l^+l^-)$$



$J/\psi K_L$

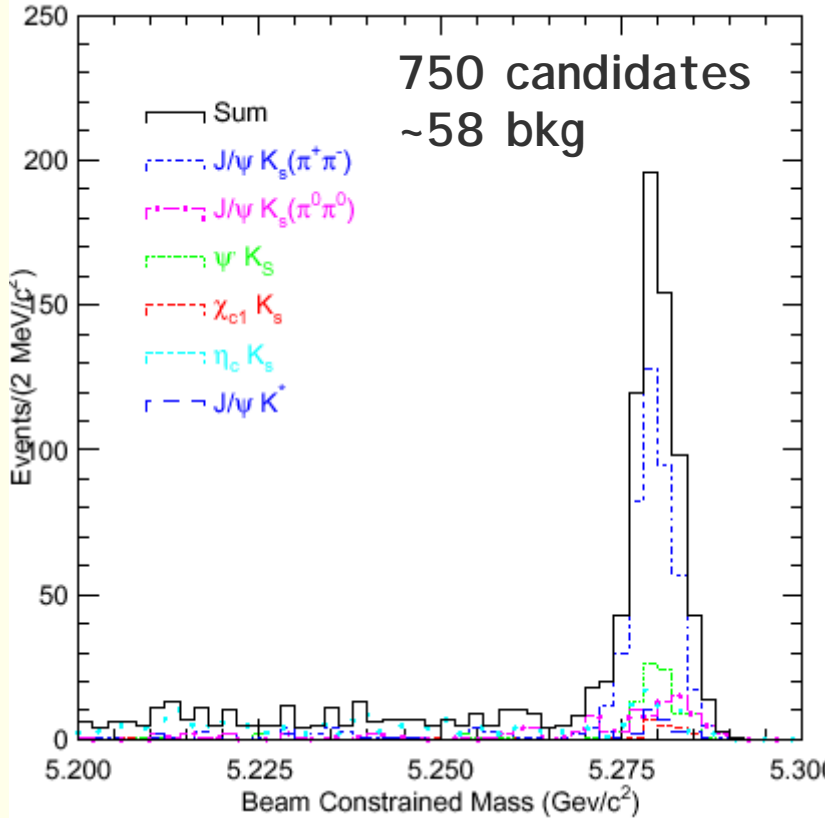
- J/ψ : {tight mass cut}
 $1.42 < p_{\psi}^* < 2.00 \text{ GeV}/c$
- K_L : {KLM/ECL cluster w/o track,
>1 KLM superlayers (resolution $\sim 3^\circ$
(1.5° if ECL)} within 45° of
expected lab direction
- Require cand to have B mass,
calculate **momentum in CMS**
(p_B^*) ($\sim 0.3 \text{ GeV}$ for signal)
- backgrounds: random (from data),
"feeddown," known
modes - estimate via MC



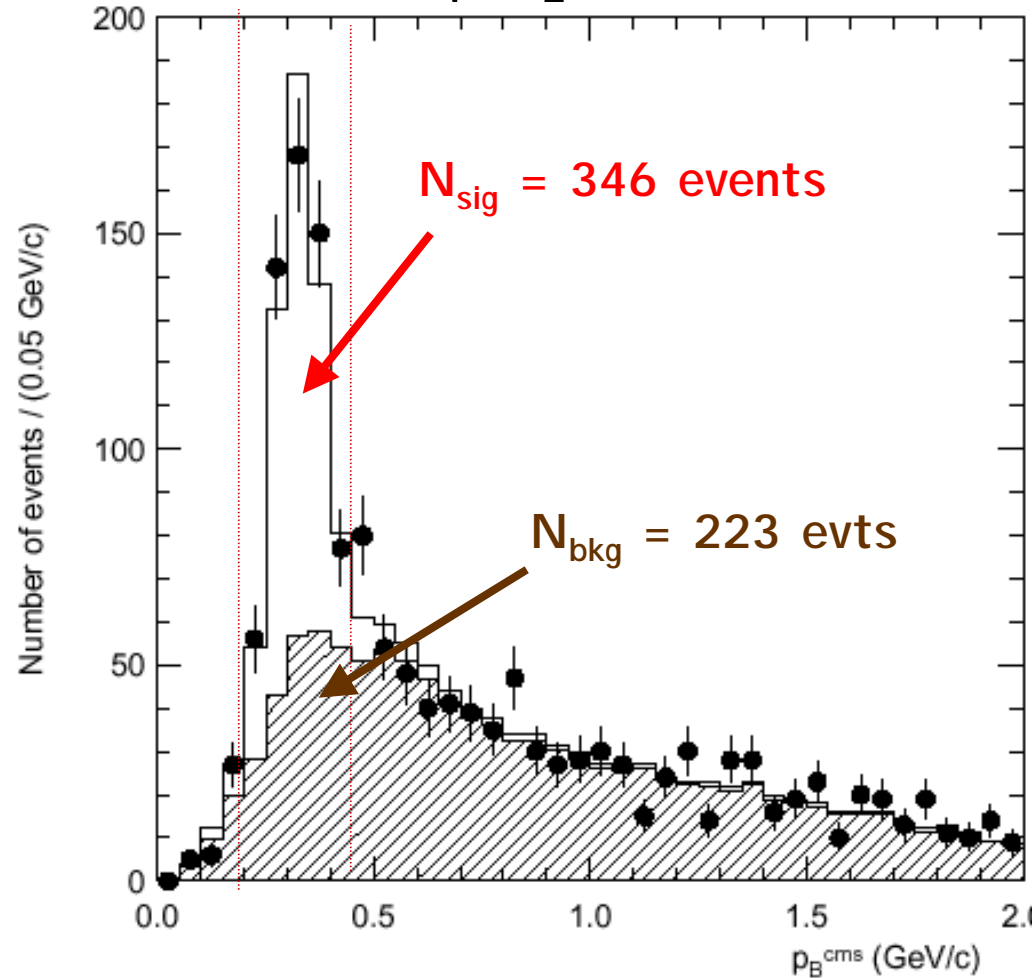


CP candidates

Fully reconstructed modes

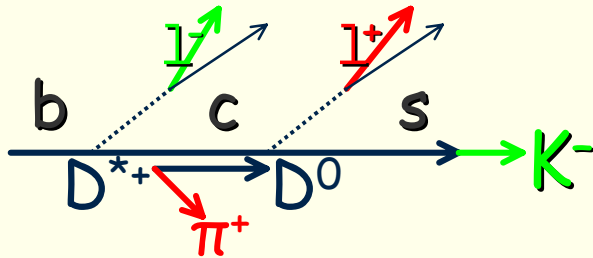


J/ψ K_L





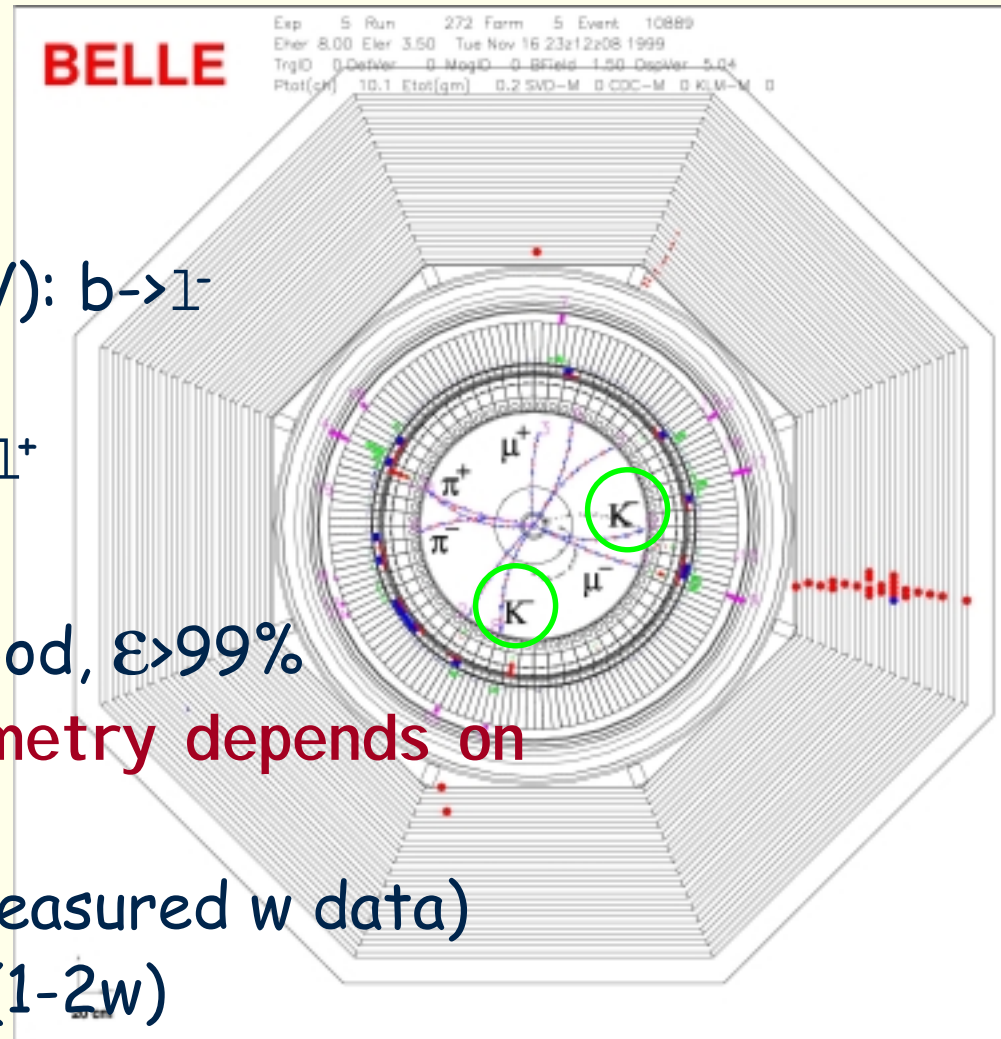
Flavor tagging



- high-p lepton ($p^* > 1.1 \text{ GeV}$): $b \rightarrow l^-$
 - net K charge $b \rightarrow K^-$
 - medium-p lepton, $b \rightarrow c \rightarrow l^+$
 - soft π $b \rightarrow c \{D^{*+} \rightarrow D^0 \pi^+\}$
- * multidimensional likelihood, $\epsilon > 99\%$

Significance of CP asymmetry depends on

- tagging efficiency ϵ
- wrong-tag fraction w (measured w data)
- effective efficiency = $\epsilon(1-2w)$

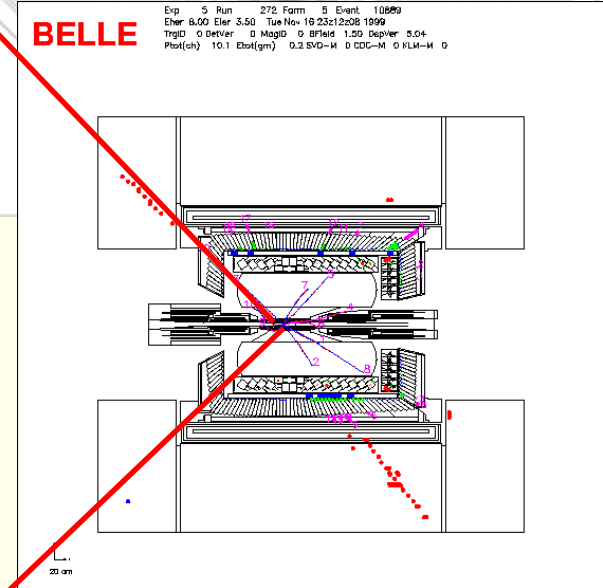
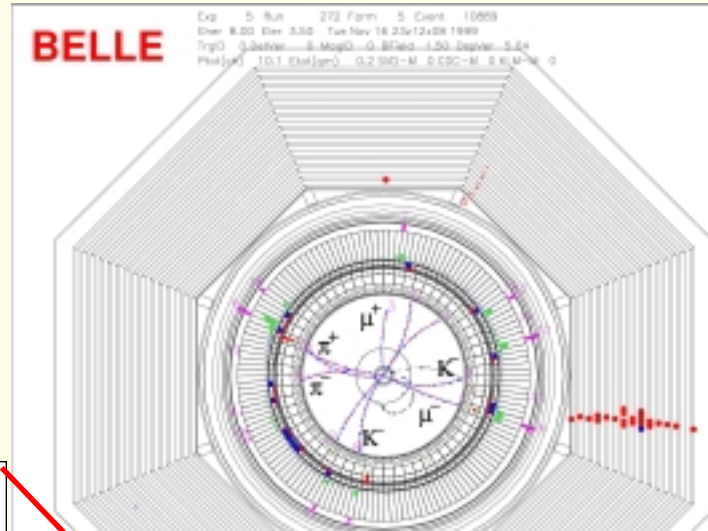
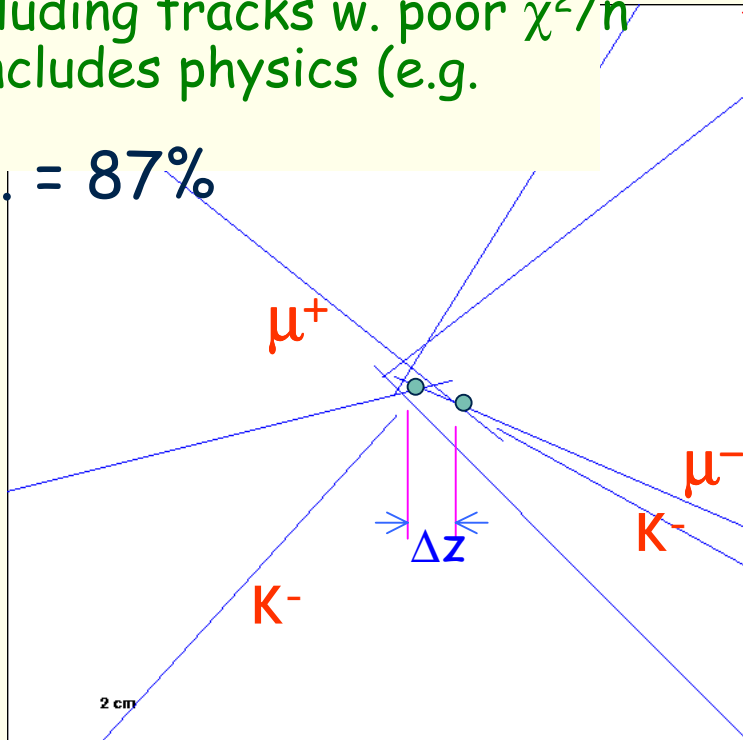




Δz : vertex reconstruction

Constrained to measured IP in $r-\phi$

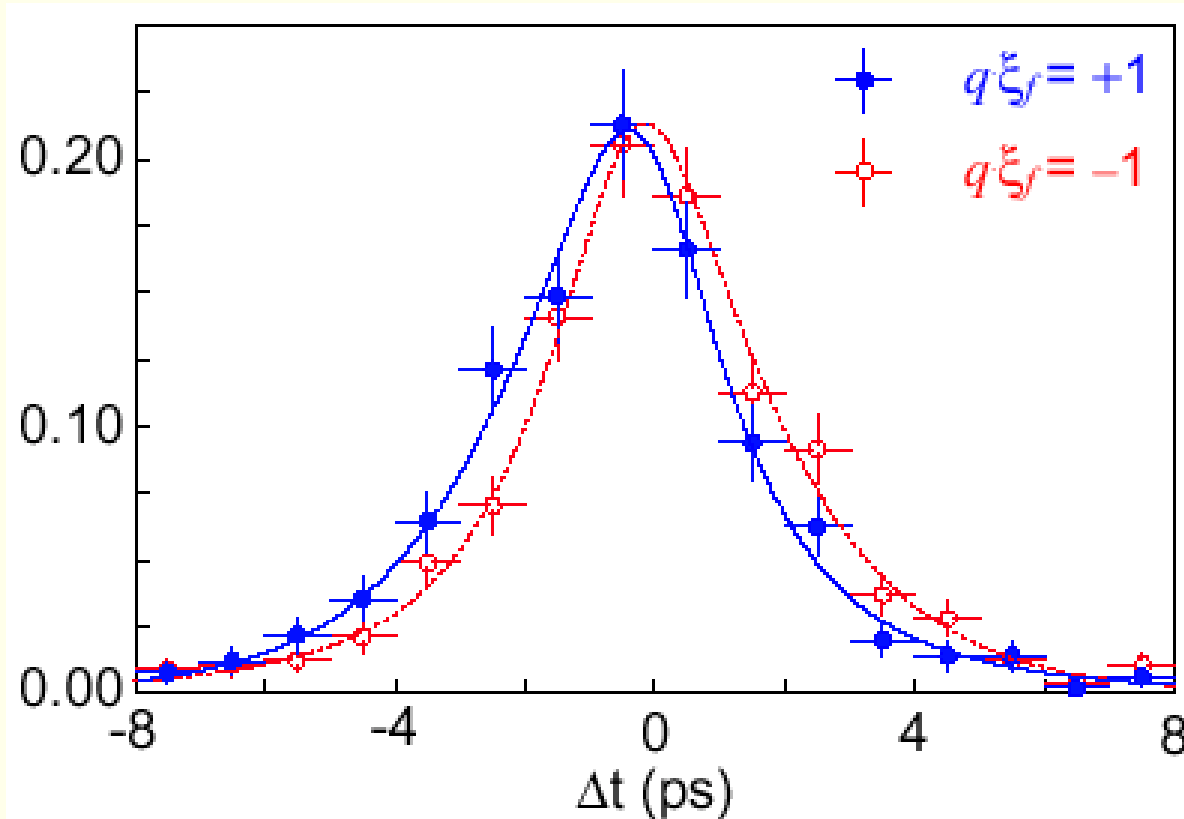
- B_{CP} : $\sigma_z \sim 75 \mu\text{m}$ (rms)
use only tracks from $J/\psi \rightarrow \eta_0$
- B_{tag} : $\sigma_z \sim 140 \mu\text{m}$ (rms)
remaining tracks, excluding K_s ;
iterate, excluding tracks w. poor χ^2/n
resolution includes physics (e.g. charm)
- Overall eff. = 87%





Raw Δt distributions

distribution in $\Delta t \sim \Delta z / \beta \gamma c$, unbinned max. likelihood fit



- CP is violated!!!
- seen in raw data
- large effect



Prepare to fit for $\sin 2\phi_1$

- B^0 lifetime = 1.548 ± 0.032 ps, $c\tau = 464 \pm 10$ μm } multiply by $\beta\gamma = 0.425$
mixing $\Delta m = 0.47 \pm 0.02$ ps^{-1} ; $cT \sim 4.0$ mm } for lab length
only ~ 1 cycle of oscillation measurable } (decay in flight)
- True CP asymmetry is diluted:
background to CP reconstruction
incorrect flavor tag rate
vertex resolution - not exactly as modeled
all need checks in data
- > Use same methods to make other (better known)
physics measurements: B^0 mixing, B lifetime,
D lifetime, null CP



Wrong tag fraction via mixing

Same fit method, but

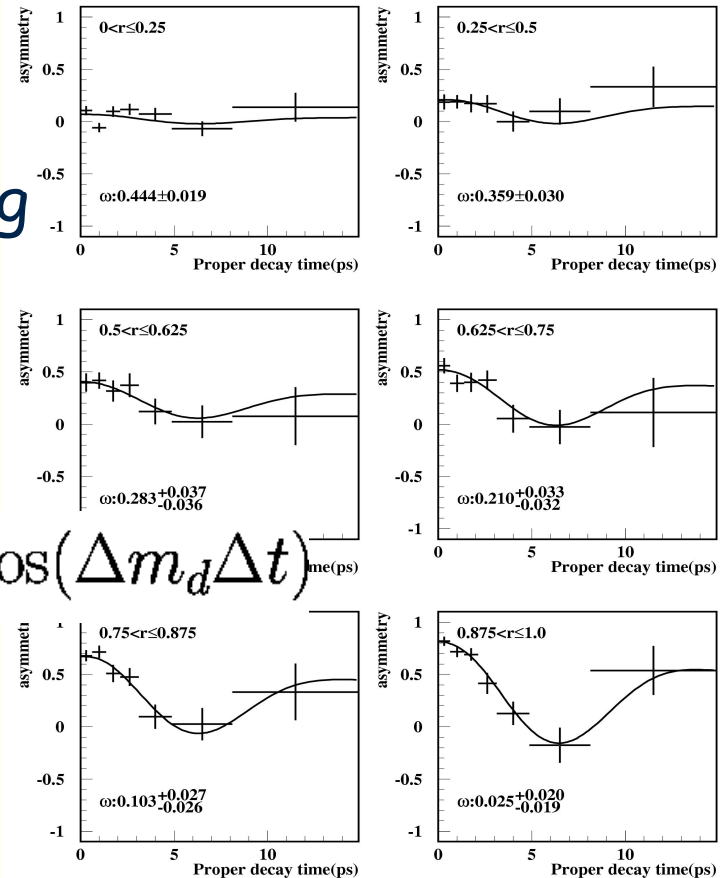
CP→flavor-specific

- $B \rightarrow \{D^{*0}\pi^+, D^{*0}\pi^-, D^{*0}\rho^+\} + \text{flavor tag}$
- separate same-, opp-flavor events
- fit to Δz : mixing asymmetry, w :

$$A_{mix} = \frac{N_{opp}(\Delta t) - N_{same}(\Delta t)}{N_{opp}(\Delta t) + N_{same}(\Delta t)} = (1 - 2w) \cos(\Delta m_d \Delta t)$$

$$\epsilon_{eff} = \sum (1 - 2w_i)^2 \epsilon_{tag, i} = (27.0 \pm 2.2)\%$$

99.4% of candidates tagged
(good agreement w MC)

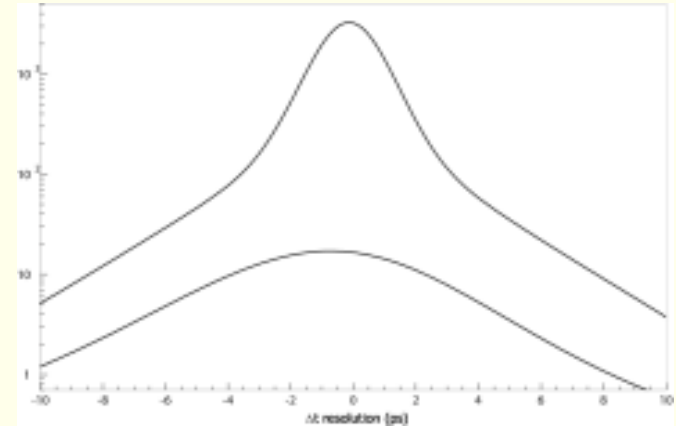


Flavor tags classified by
(MC) Purity - 6 bins



Δt resolution function

- Double Gaussian, parameters calculated event-by-event, includes effects of
 - detector resolution
 - poorly measured tracks
 - bias from e.g. charm
 - approximation of $\Delta t = \Delta z / \beta \gamma c$
- form, parameters from
 - Monte Carlo
 - fits for $D^0 \rightarrow K^- \pi^+$, $B \rightarrow D^* \ell \nu$ lifetimes
- validate: B lifetime, same fitting



tail fraction: 1.8%

$$\tau_0 = 1.55 \pm 0.02 \text{ ps} \quad (\text{PDG2000: } 1.548 \pm 0.032 \text{ ps})$$

$$\tau_+ = 1.64 \pm 0.03 \text{ ps} \quad (\text{PDG2000: } 1.653 \pm 0.028 \text{ ps})$$



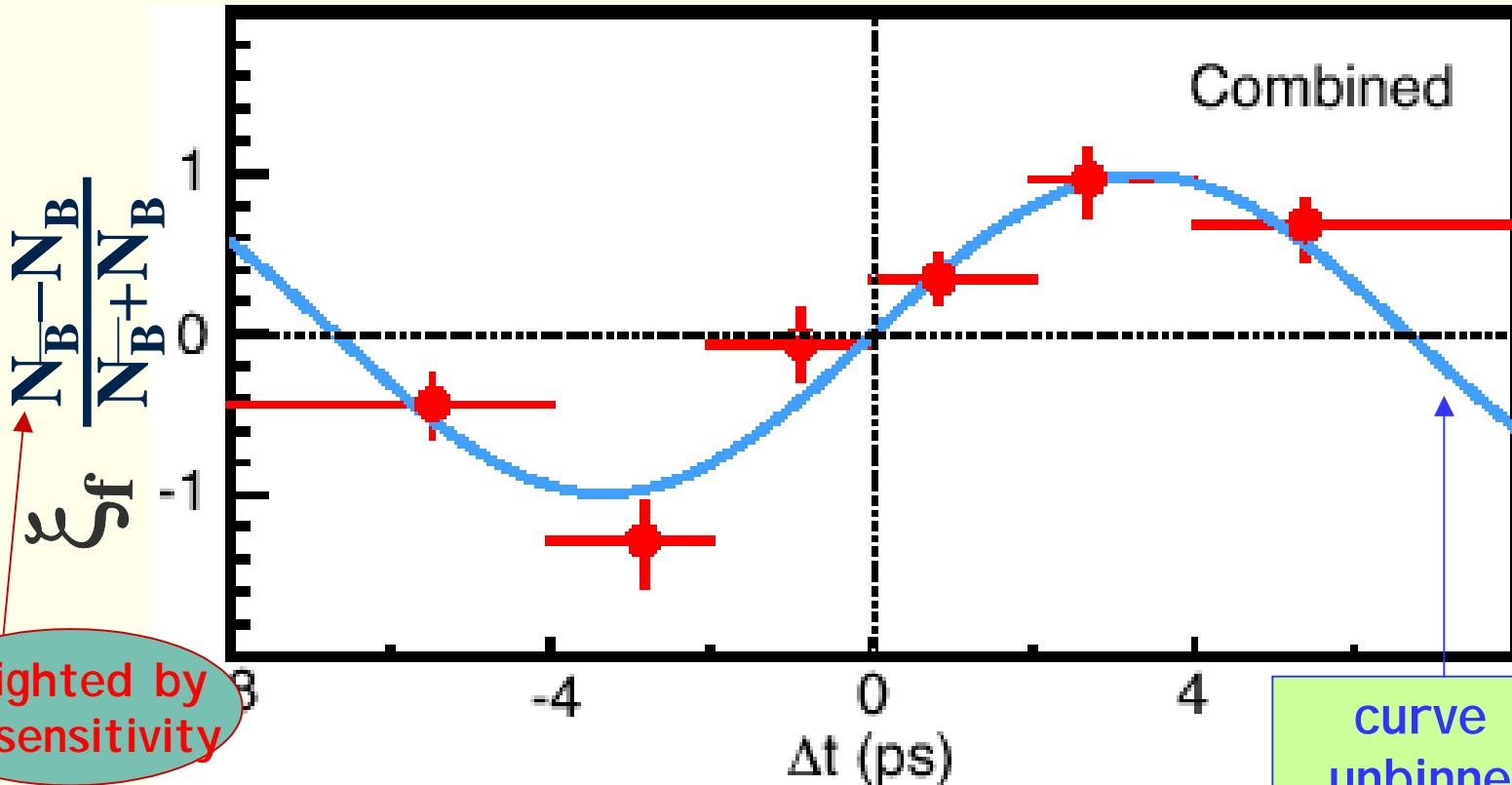
Fitting Δt distribution

- distribution in $\Delta t \sim \Delta z / \beta \gamma c$
- unbinned max. likelihood fit, includes
 - signal root distribution (analytic)
 - wrong tag fraction (const)
 - background: right & wrong tag (MC, parametrized)
 - detector & tagging Δz resolution
(parametrized, evt-by-evt)



Results

All modes combined: $\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) + 0.06(\text{sys})$



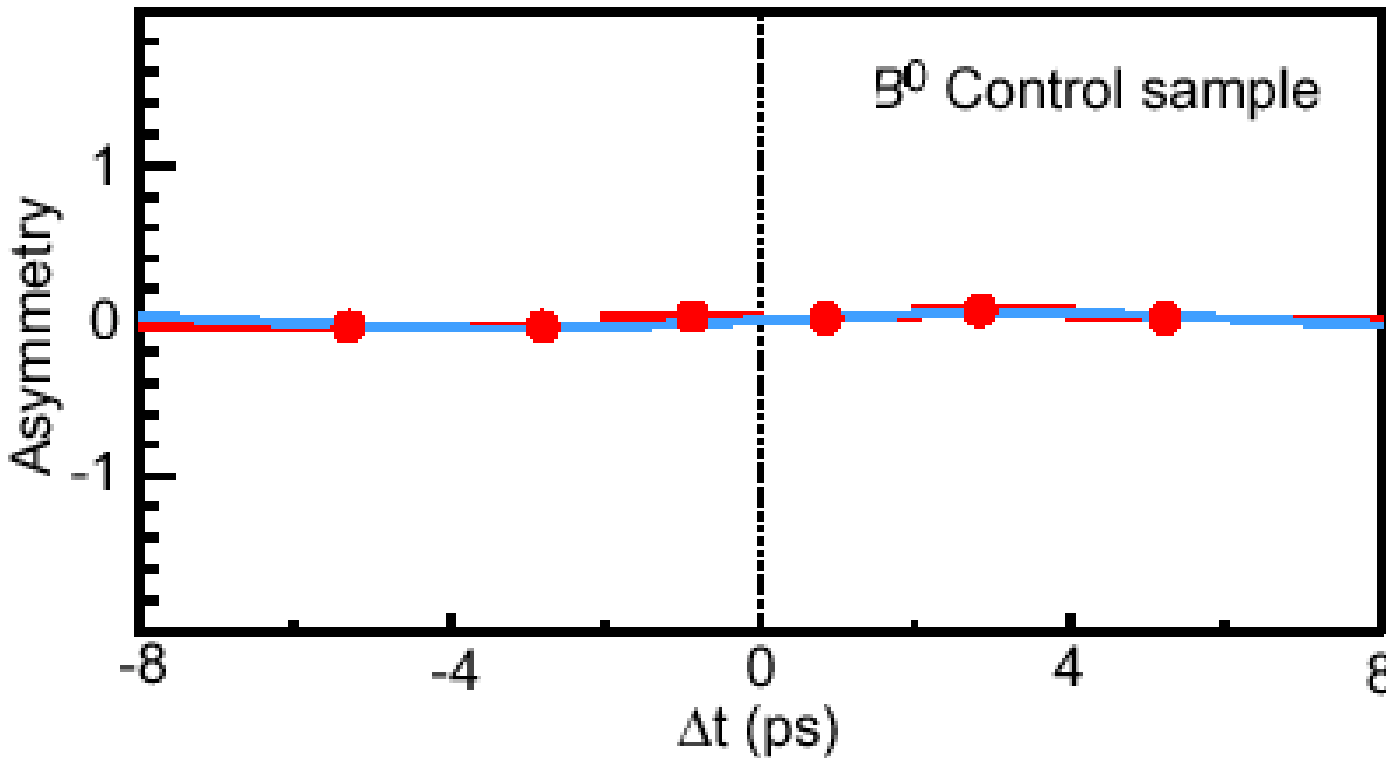
weighted by CP sensitivity

curve from unbinned fit



Control sample: $B^0 \rightarrow$ non-CP states

use: $B^0 \rightarrow D^{(*)-} \pi^+$, $D^{*-} \rho^+$, $D^{*-} l^+ \nu$, $J/\psi K^*(K^+ \pi^-)$



“ $\sin 2\phi_1$ ”

0.05 ± 0.04

(statistical error only)

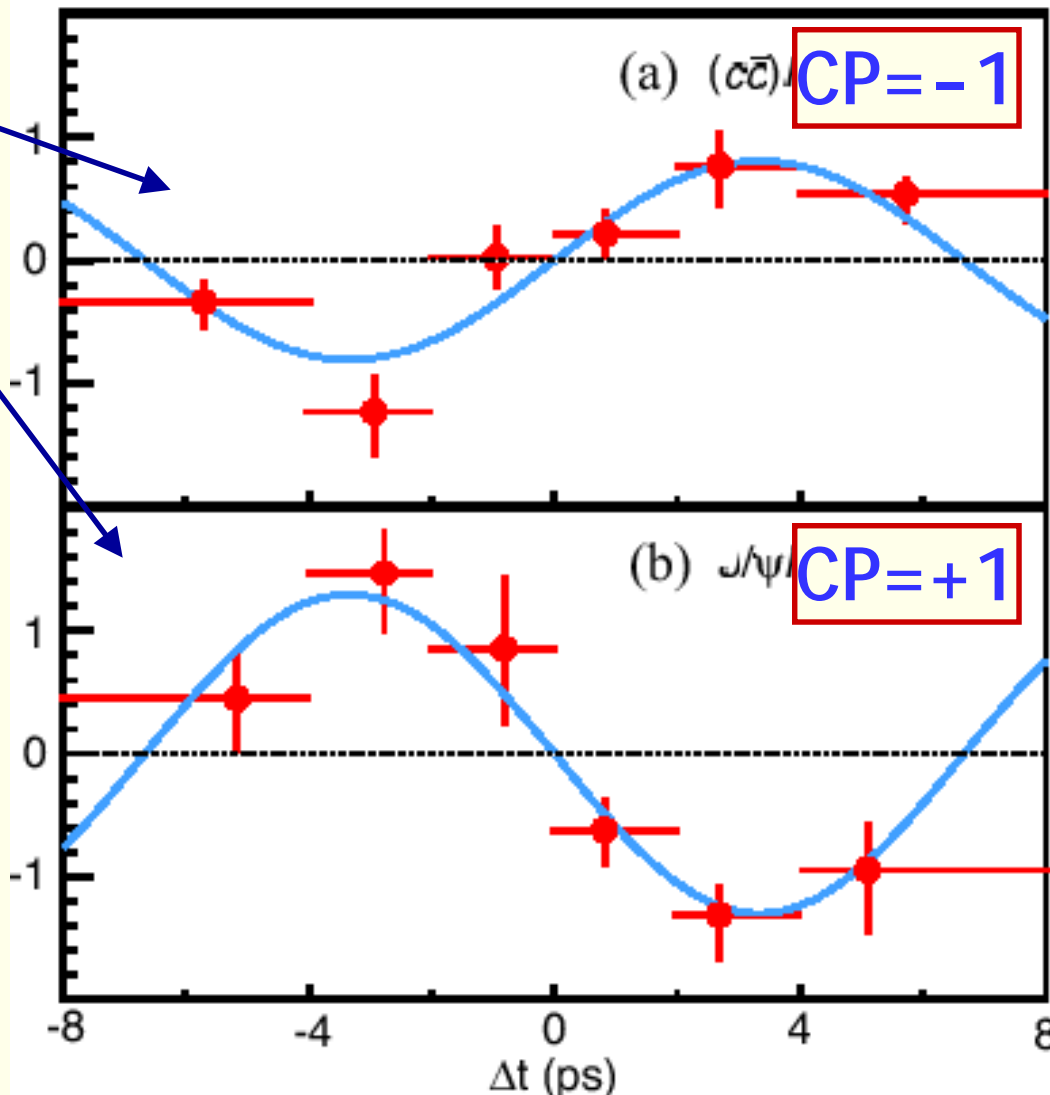


fit CP -1 and CP+1 separately:

opposite!!

$$\frac{N_{B^-} - N_{\bar{B}^-}}{N_{B^-} + N_{\bar{B}^-}}$$

weighted by CP sensitivity



$$\frac{\sin 2\phi_1}{0.84 \pm 0.17}$$

$$1.31 \pm 0.23$$

(statistical errors only)

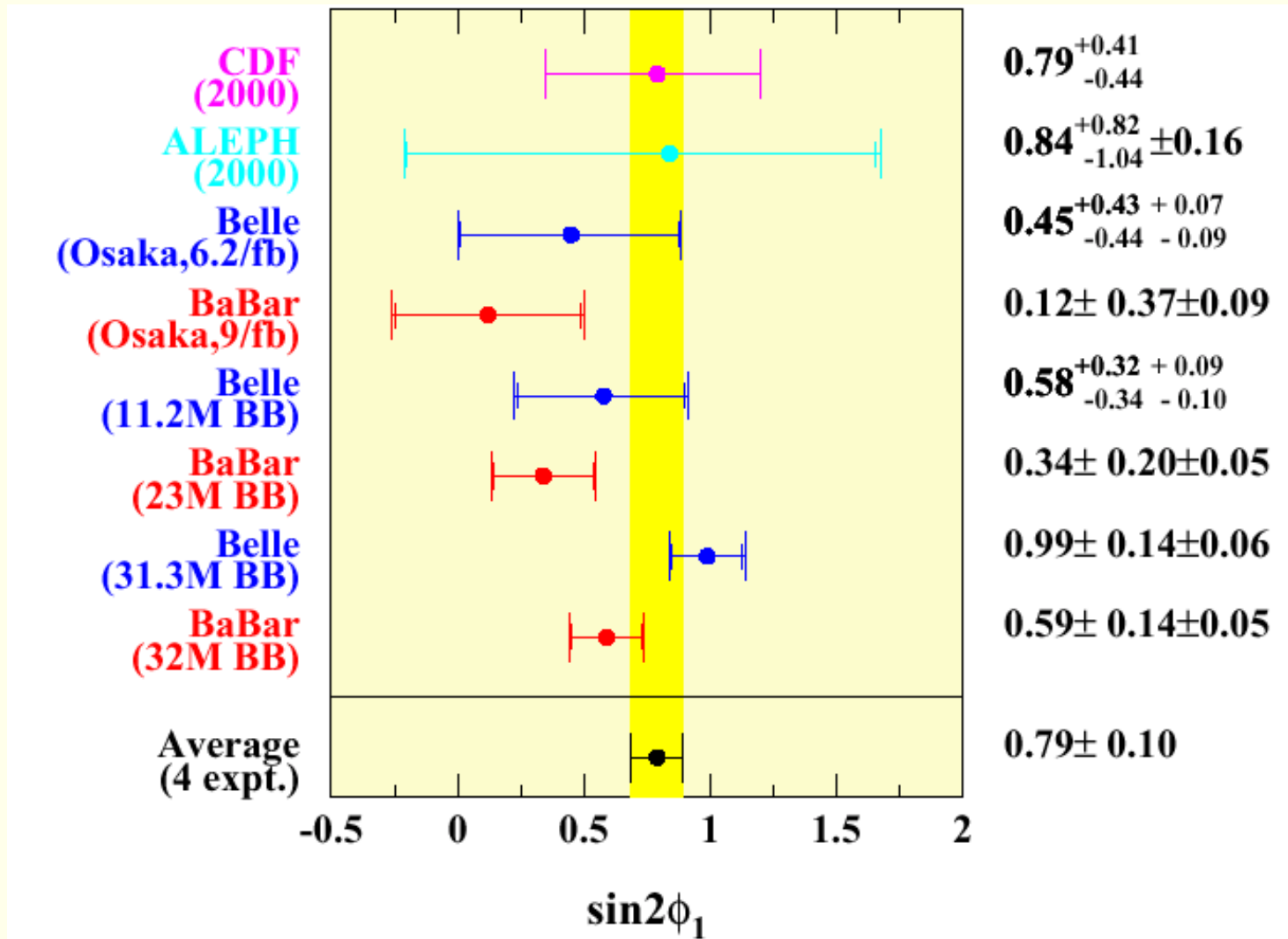


Systematic errors

Vertex algorithm	± 0.04
Flavor tagging	± 0.03
Resolution function	± 0.02
K_L background fraction	± 0.02
Background shapes	± 0.01
Δm_d and τ_{B0} errors	± 0.01
Total	± 0.06



Compare with other experiments

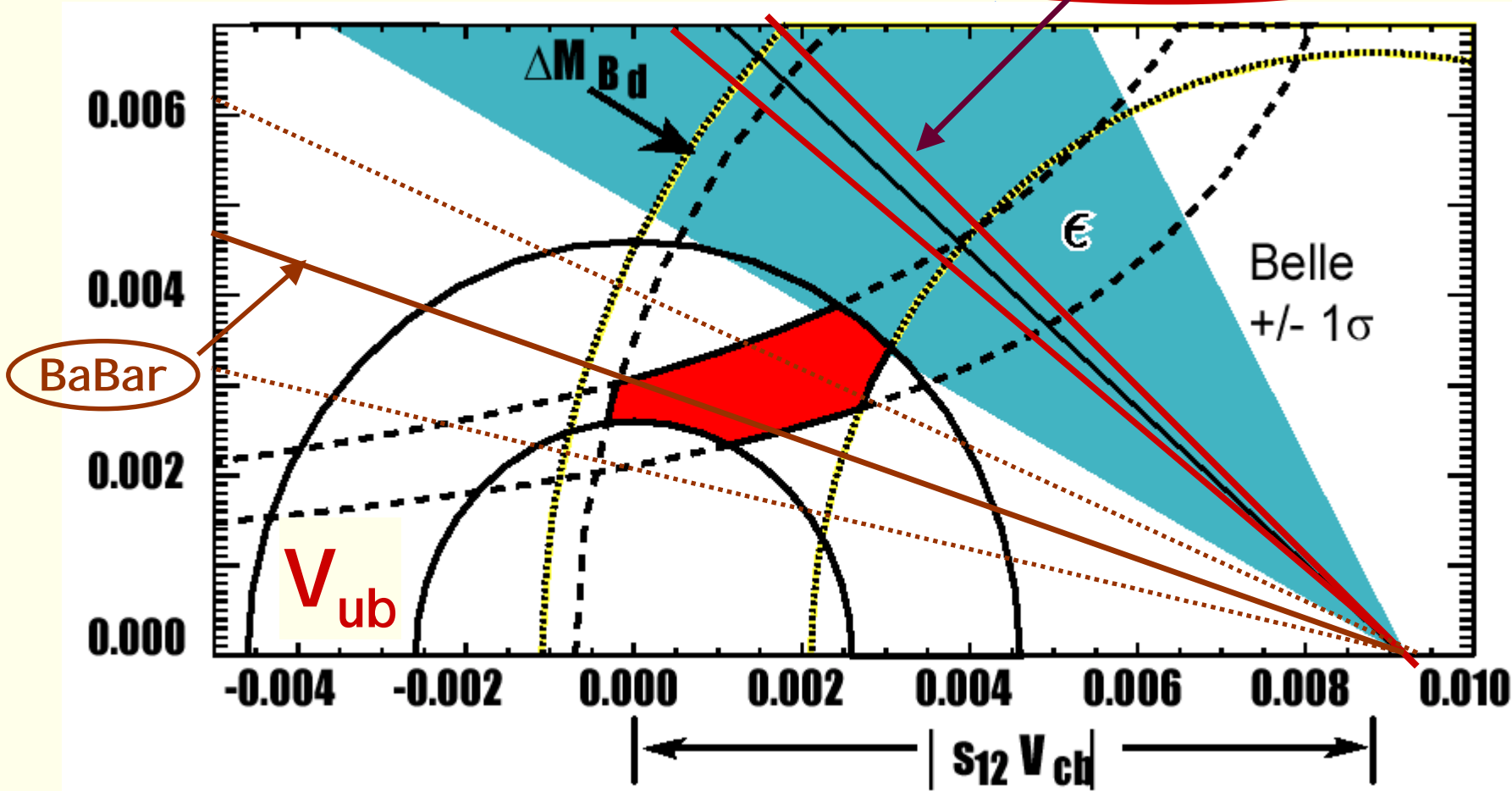




Result in context

(locating tip of unitarity triangle)

Belle's 1 σ band (two sol'ns)





Summary/Prospects

Successful run of Belle in 2000-1

- $\sin 2\phi_1$: 30.5 fb⁻¹ on $\Upsilon(4S)$, 1137 tagged events
- 19 papers published or submitted

Next

- higher precision on $\sin 2\phi_1$
data as of 1/23/02 - 48 fb⁻¹; anticipate 100 fb⁻¹ by summer
- Lum: peak $5.5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$; 24 hrs 311 pb⁻¹;
month 6120 pb⁻¹
- other angles - need >300 fb⁻¹ - within sight!