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^- -> $\Upsilon(4S)$
- Belle/Babar experiment

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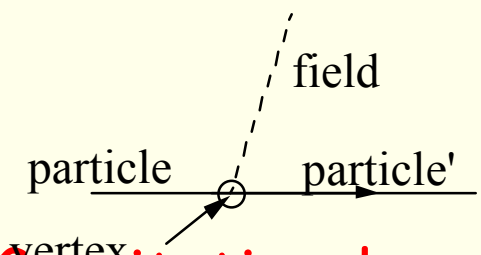
Symmetry of Physical Laws

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

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

Add interactions: emission/absorption of field quantum

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



Forces: Strong, Electromagnetic, Weak, Gravitational

coupling ~ 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 x 2 types x 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	**u**p	**C**harm	**t**ruth
	-1/3	**d**own	**S**trange	**b**eauty

Weak couplings

Z^0

"neutral current"

$\Delta Q = 0$

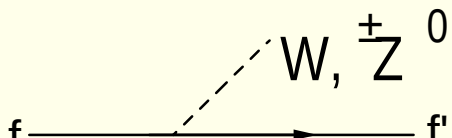
$l^{\pm} \leftrightarrow l^{\pm}$

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

NO generation x-ing

-> no flavor-changing

single coupling strength



$W^{\pm}$

"charged current"

$\Delta Q = \pm 1$

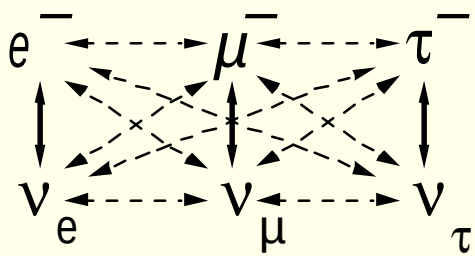
$l^{-} \leftrightarrow \nu$

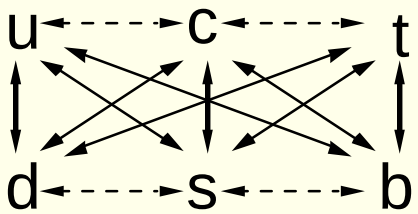
$q^{+2/3} \leftrightarrow q'^{-1/3}$

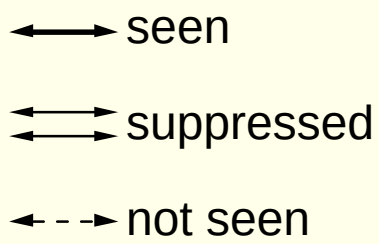
(small) generation x-ing,

quark only

all different strengths







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

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

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

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

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):

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

Unitarity condition:

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

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

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

(ρ, η): "unitarity triangle"

Self-consistent if CKM is correct

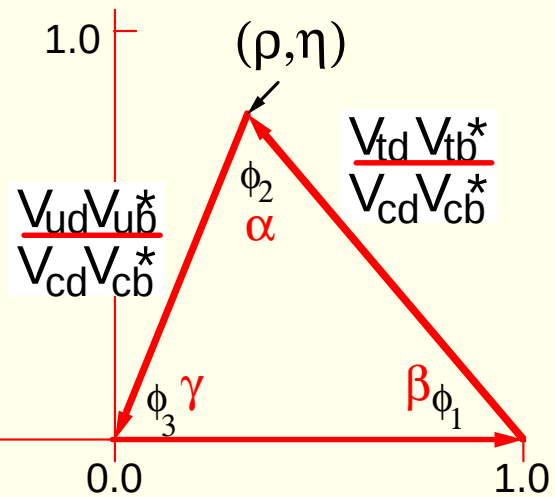
from decay rates,

$\lambda = 0.220 \pm 0.002$

$A = 0.81 \pm 0.08$

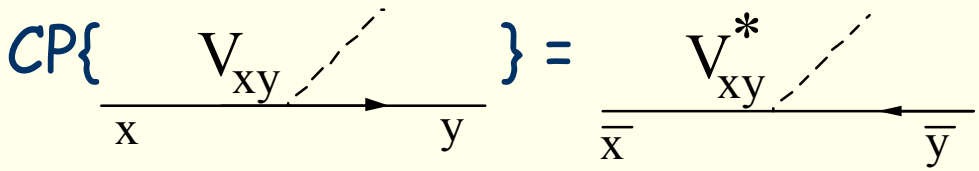
$|\rho-i\eta| = 0.36 \pm 0.09$

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



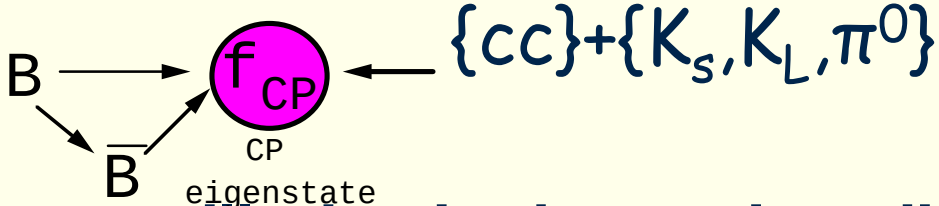
Complex couplings revealed via CP asymmetry

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



– need interference between processes:

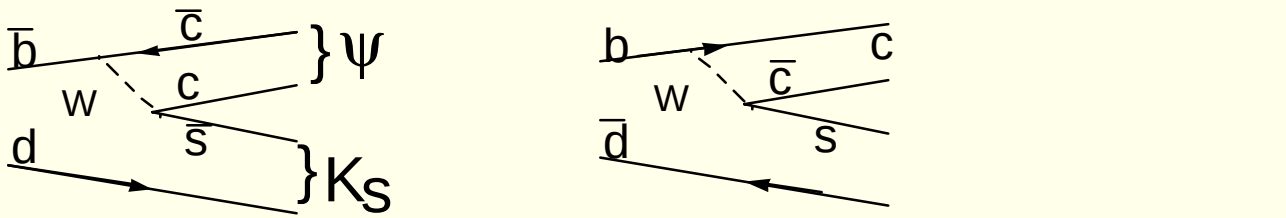
e.g., decays to CP eigenstate - paths w/wo mixing interfere



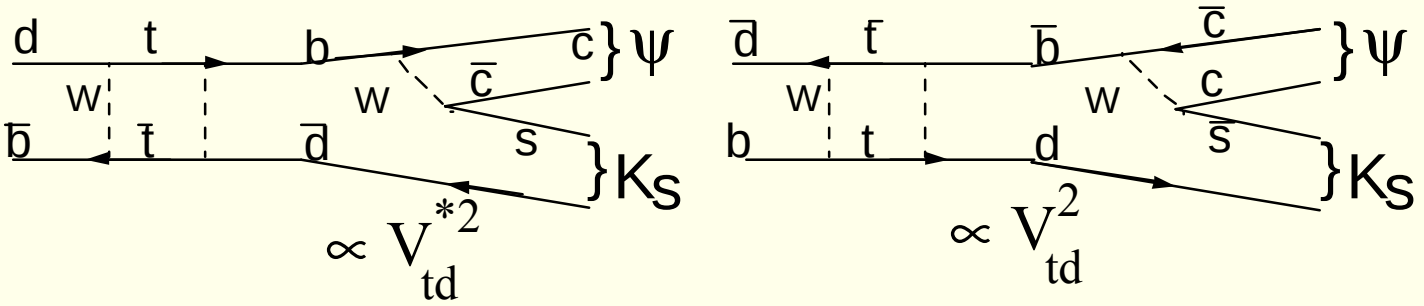
-> CP-dependent oscillation in decay time distributions

CP Asymmetry of B -> J/ψ K_s

tree (real V_{ij})



mixing+tree



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

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

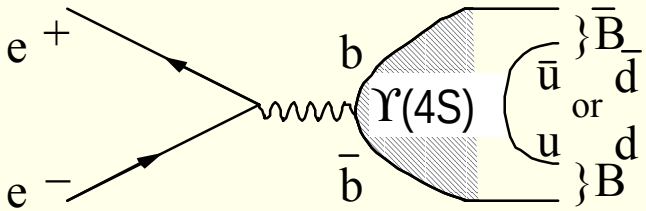
$$\eta_b = \begin{pmatrix} +1 \text{ if } B_{t=0} = B^0 \\ -1 \text{ if } B_{t=0} = \bar{B}^0 \end{pmatrix} \qquad \eta_{CP} = \begin{pmatrix} -1 \text{ if } CP \text{ odd} \\ +1 \text{ if } CP \text{ even} \end{pmatrix}$$

* No theoretical uncertainty

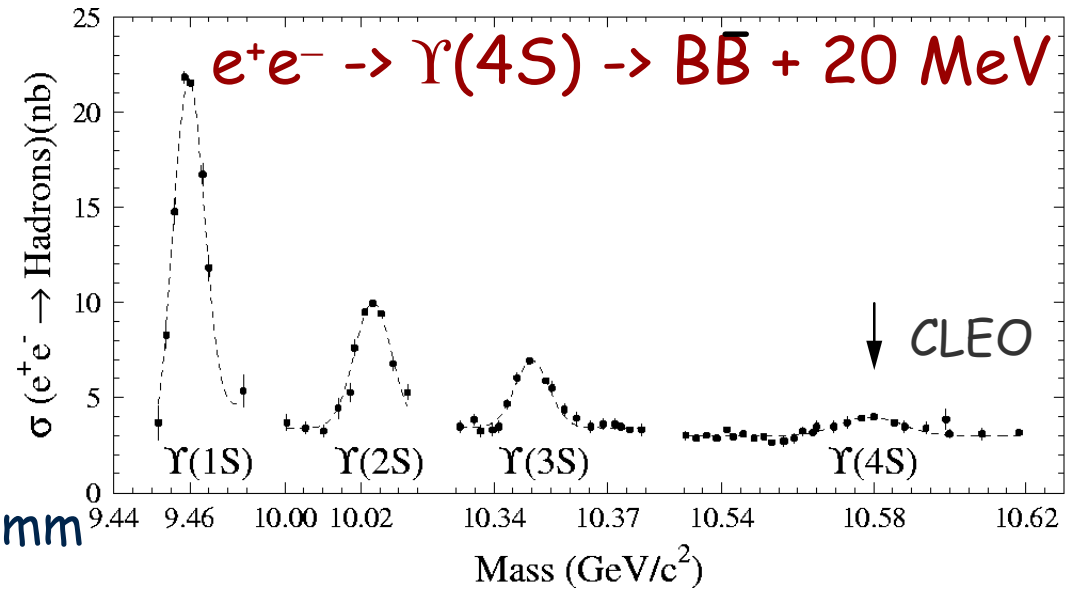
Measure time dependence - what's needed?

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

$B\bar{B}$ pair production: Upsilon



$B^+ : B^0 \sim 1:1$



KEKB:

8.0 GeV e^- + 3.5 GeV e^+

IP size = 77μmx2.0μmx4.0mm

Event rate

Cross section ~ 1 nb = 10^{-33} cm^2

$$\frac{dN}{dt} = \sigma \times L \sim 10\ s^{-1} \sim 10^8 yr^{-1}$$

← Luminosity (collision rate)

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

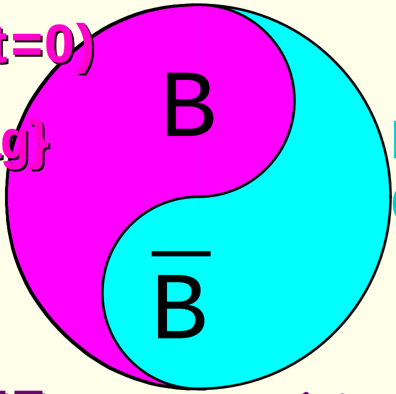
Currently@Belle: 3×10^7 $B\bar{B}$ events (published), 4.8×10^7 on tape

Time measurement at ϒ(4S)

ϒ(4S): CP=-1, conserved

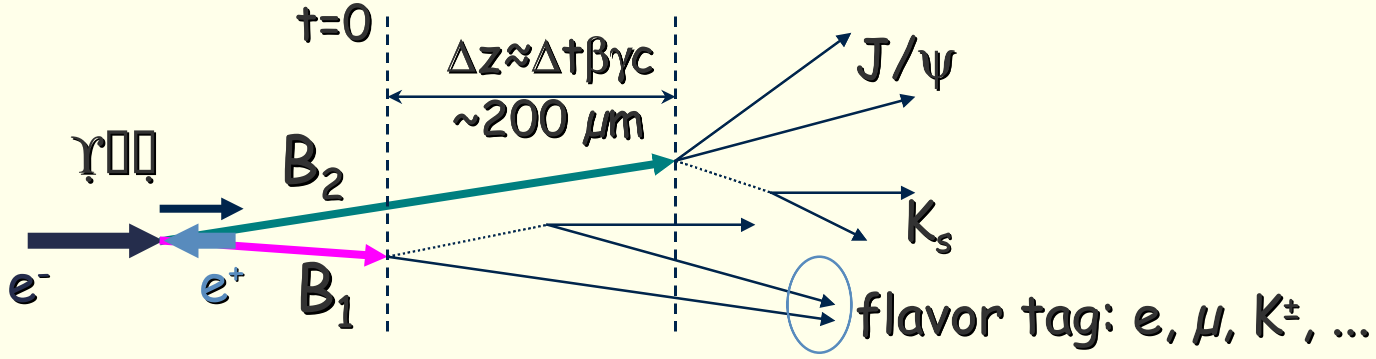
until first B decay (t=0)

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



Reconstruct CP=±1 mode @ t=Δt

Δ[illegible]$^{+}e^{-}$ -> ϒ(4S)



Detector: e.g. Belle

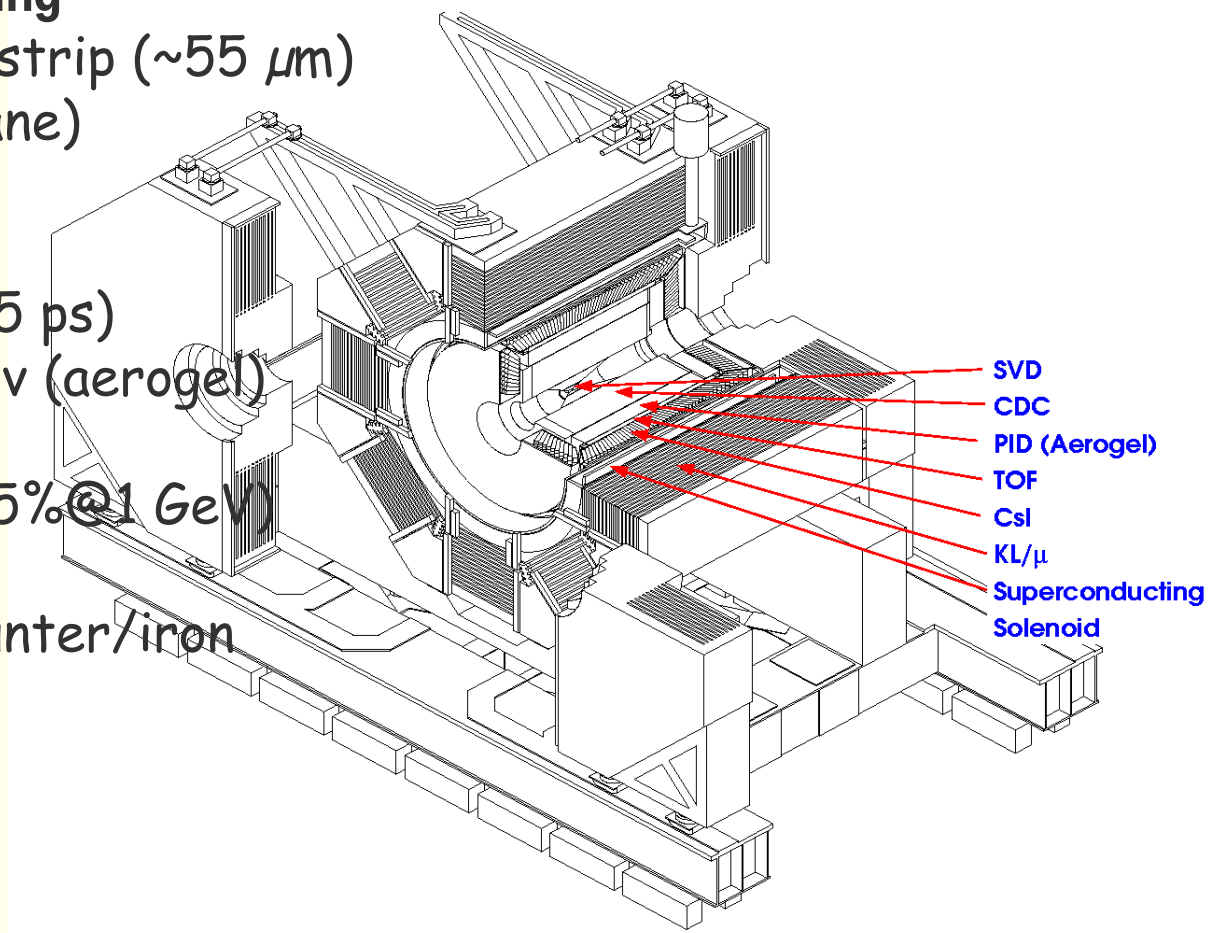
Designed to measure CP asymmetry

Charged tracking/vertexing
- SVD: 3-layer DSSD Si μstrip (~55 μm)
- CDC: 50 layers (He-ethane)

Hadron identification
- CDC: dE/dx (~7%)
- TOF: time-of-flight (~95 ps)
- ACC: Threshold Cerenkov (aerogel)

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

Muon/KL
- KLM: Resistive plate counter/iron



Belle Collaboration

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

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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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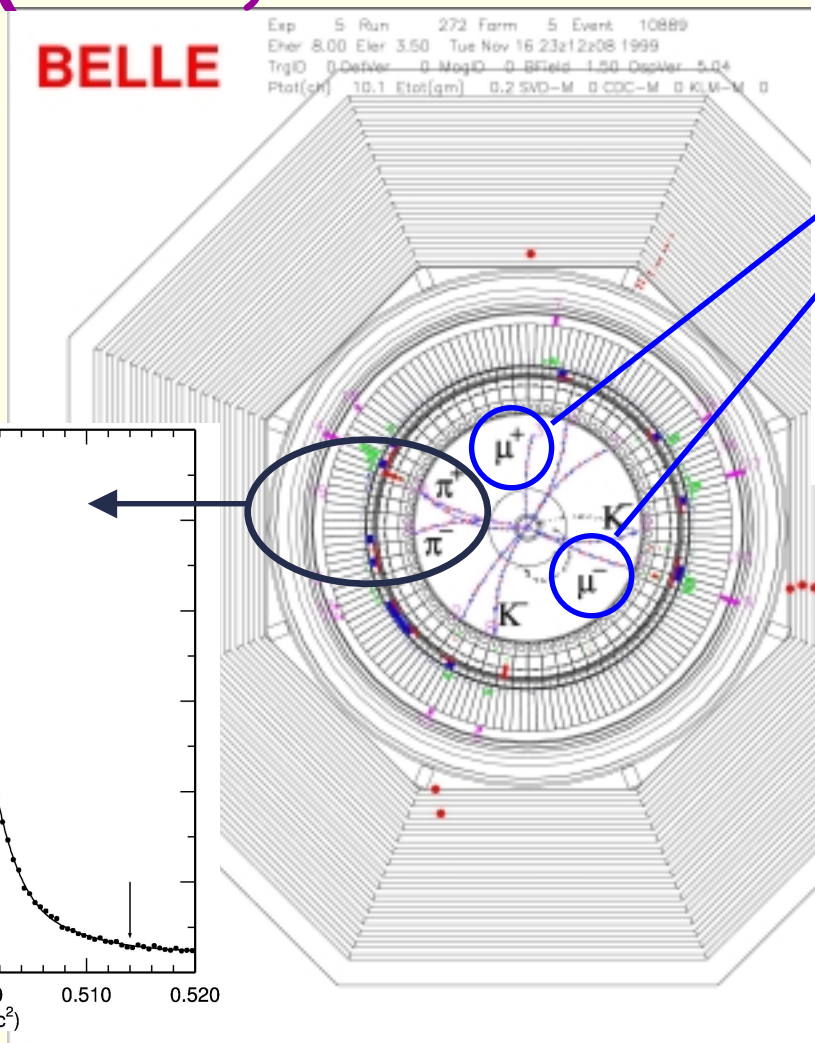
274 authors, 45 institutions

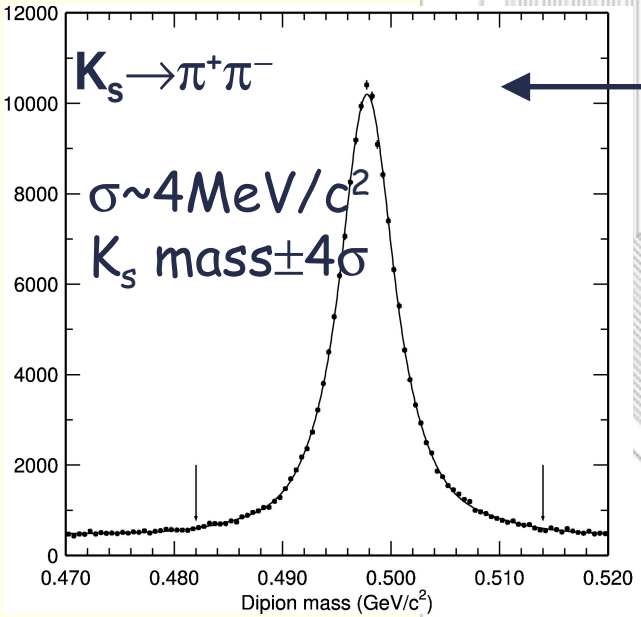
many nations

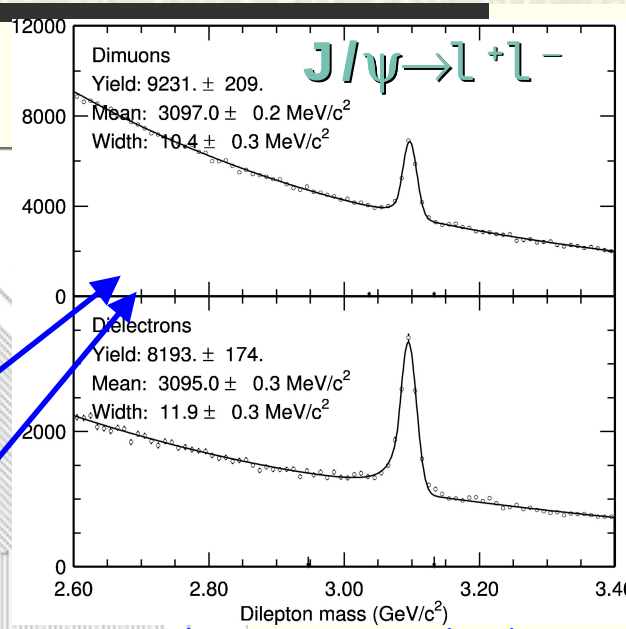
CP mode reconstruction

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

"golden mode"



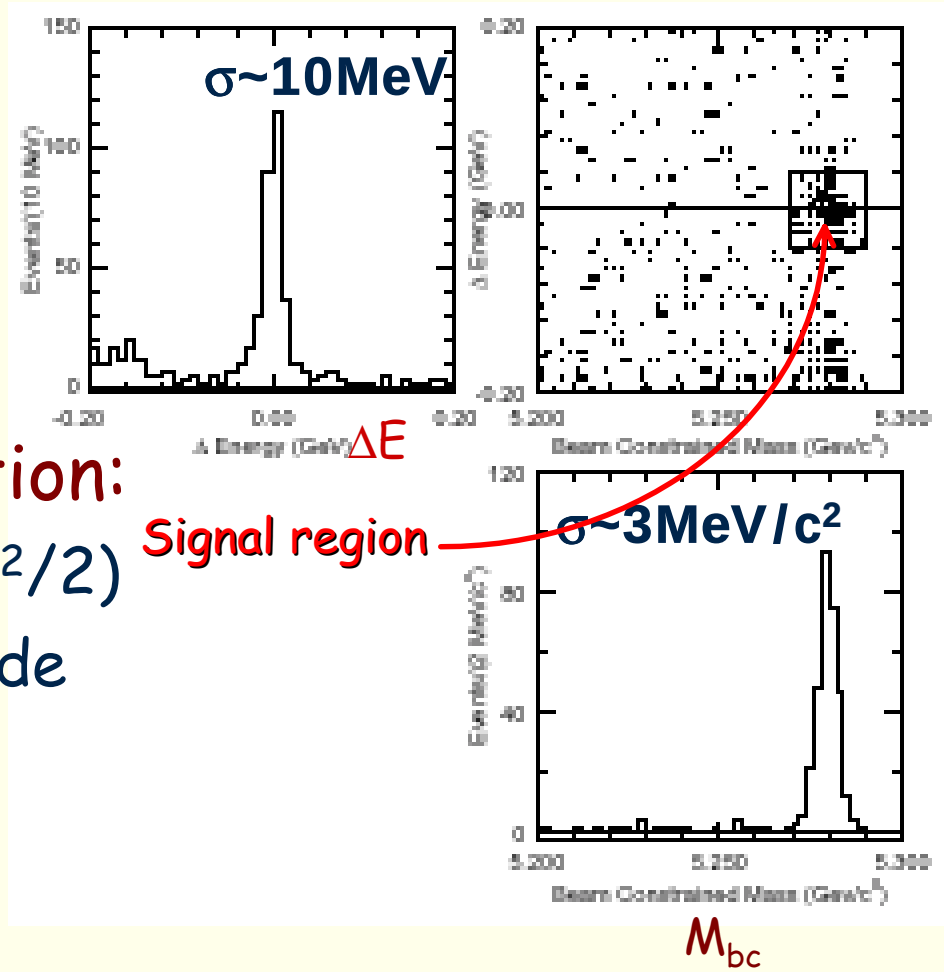




1lepton+1"not-hadron"

$B^0 \to J/\psi\ K_s$ (continued)

457 events
~3% background



Kinematics for final selection:

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

10-50 MeV res, depends on mode

M_{bc} (Beam-constrained mass)

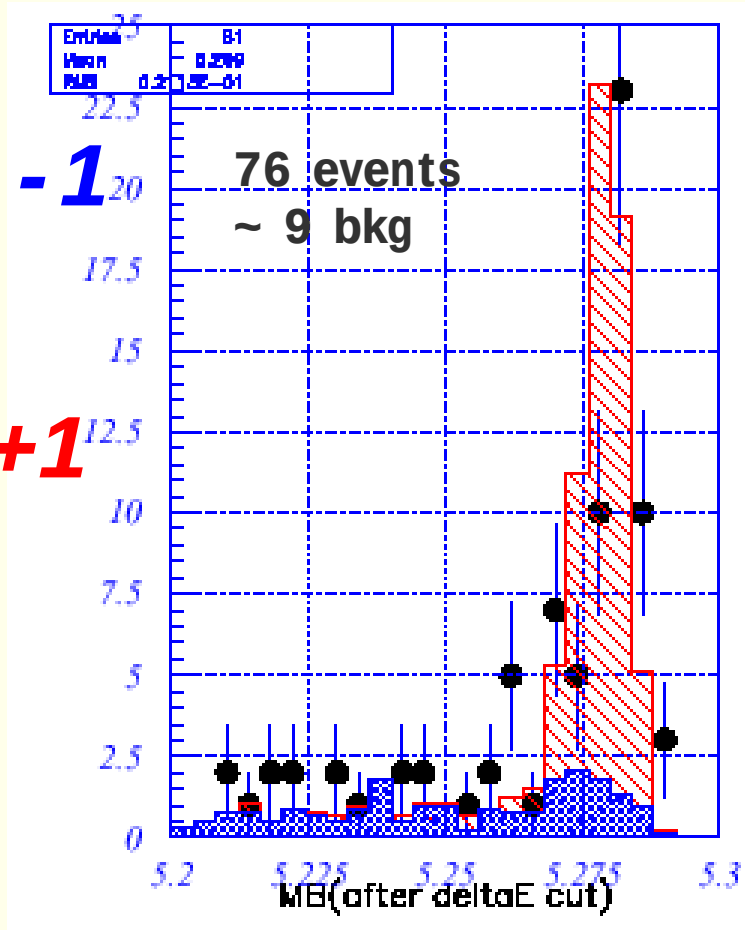
$M_{bc} \equiv (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$

Other charmonium+K

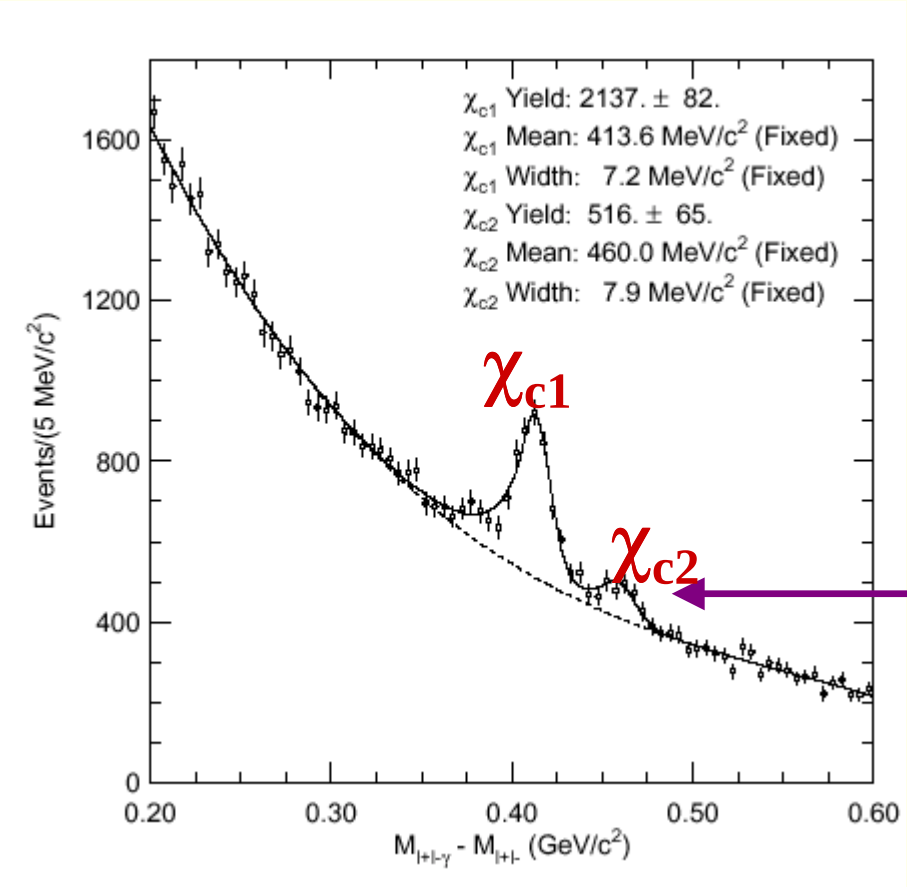
$B^0 \to J/\psi\ K_s(\to \pi^0\pi^0)$

$J/\psi\ K_S(\to \pi^+\pi^-\ \&\ \pi^0\pi^0)$
$\psi(2S)(\to l^+l^-\ \&\ J/\psi\pi^+\pi^-)\ K_S$
$\chi_{c1}(\to J/\psi\gamma)\ K_S$
$\eta_c(\to K_S K^+\pi^-, K^+K^-\pi^0)\ K_S$
$\xi_f = -1$

$J/\psi\ K_L$
$J/\psi\ K^{*0}\ (\to K_L\pi^0)$ (mostly)
$\xi_f = +1$



Other charmonium

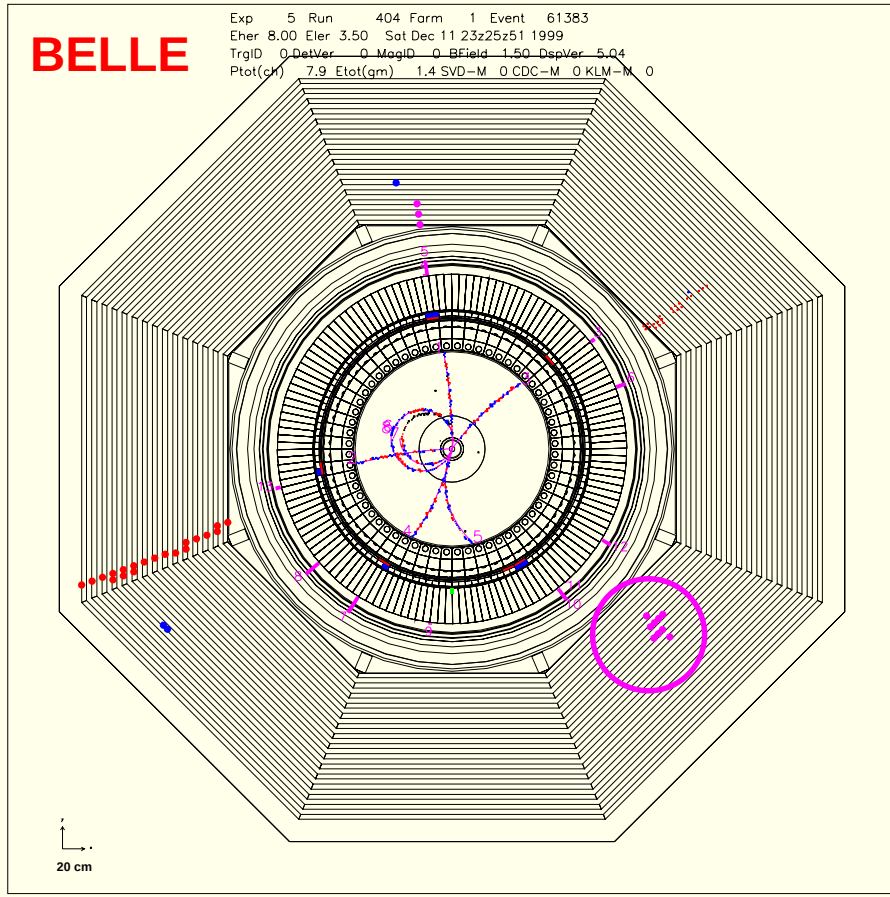


1st observation of inclusive $B \to \chi_{c2} X$

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

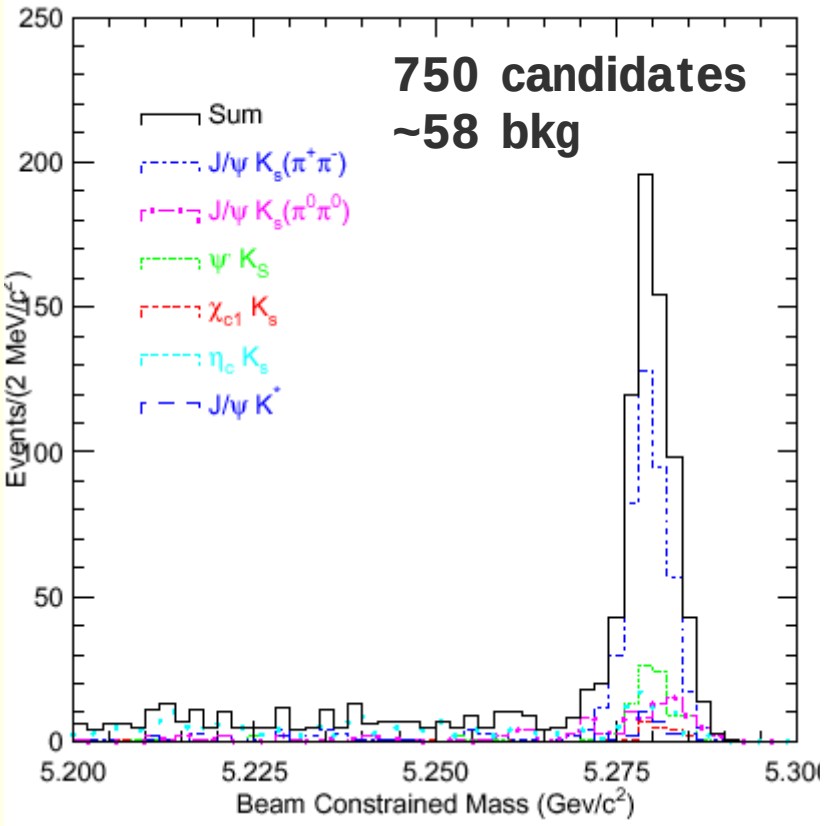
$\tilde{B}\tilde{B}$ J/ψ K_L

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

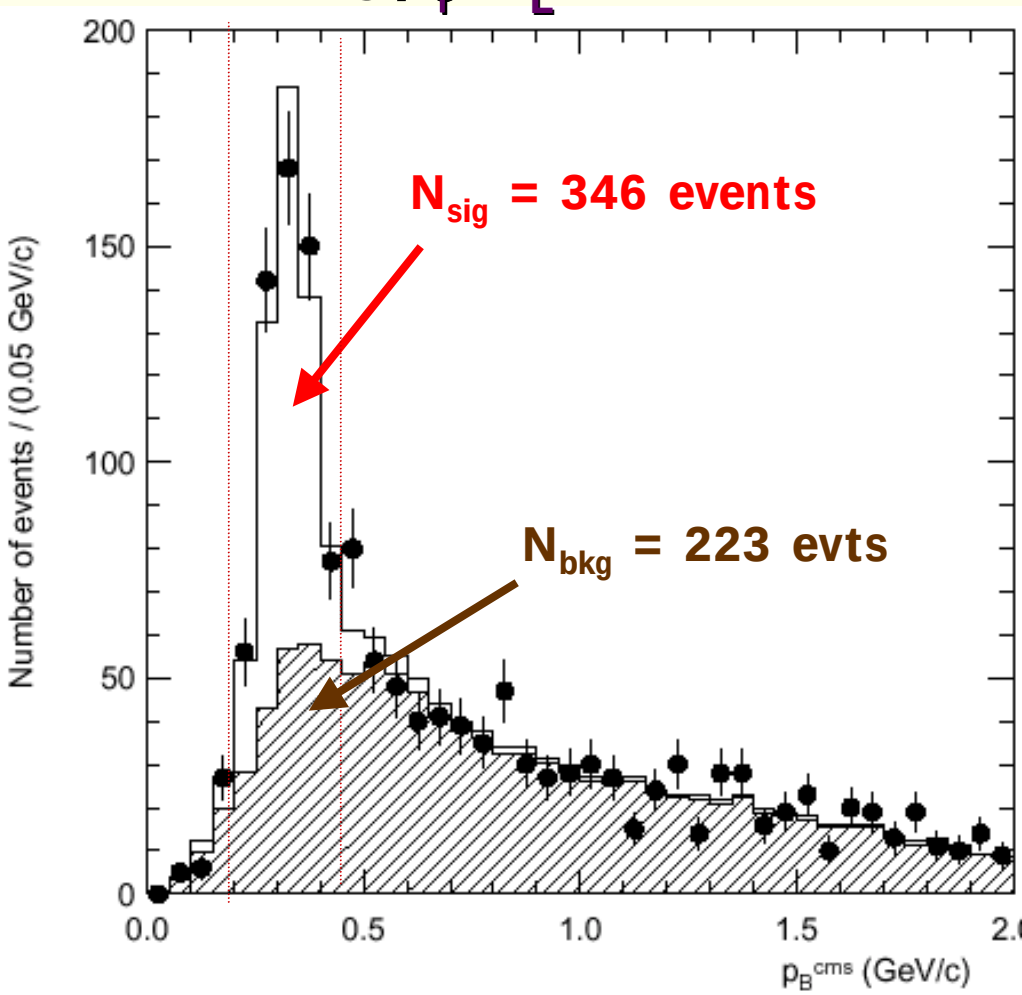


CP candidates

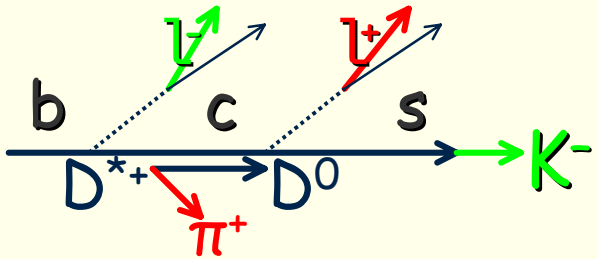
Fully reconstructed modes



J/ψ K_L



Flavor tagging

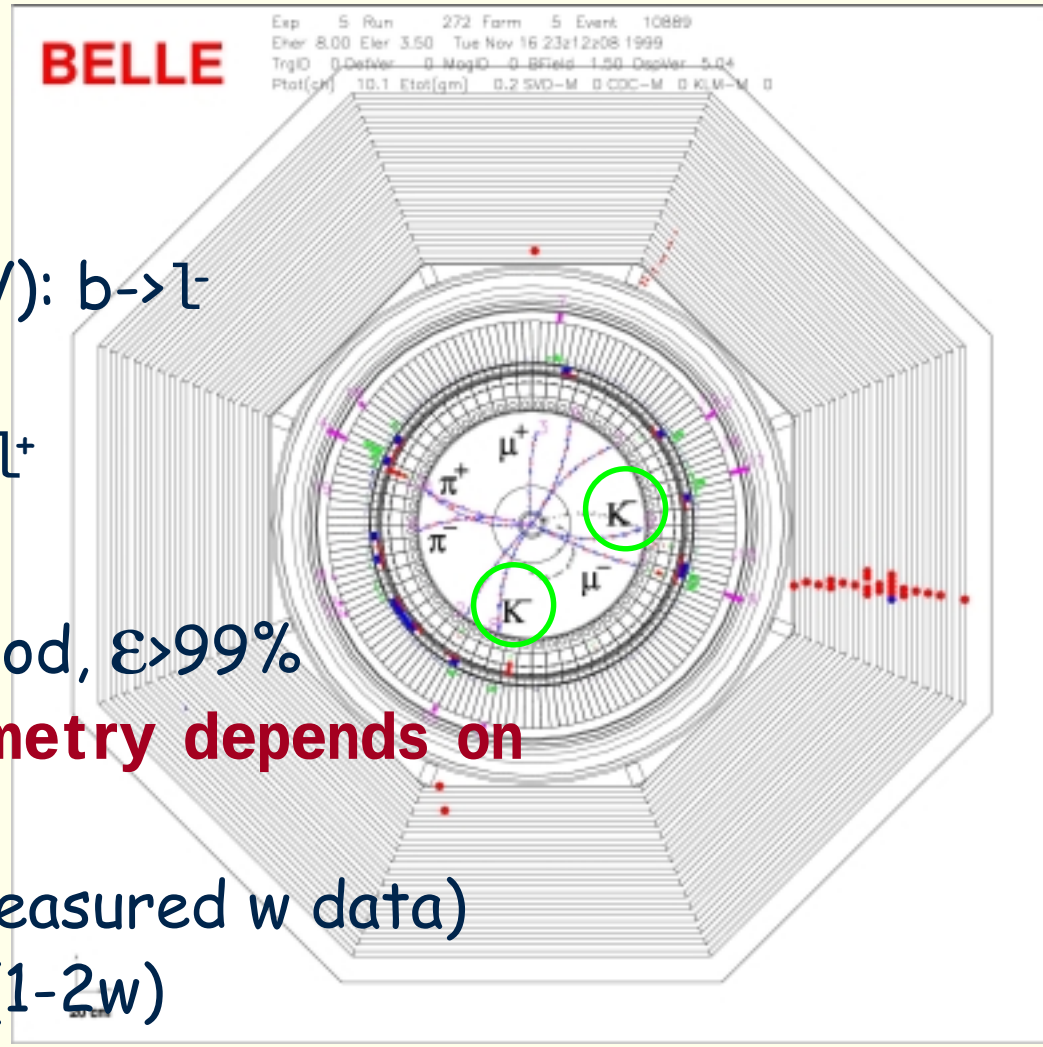


- high-p lepton (p*>1.1 GeV): b->l⁻
- net K charge b->K⁻
- medium-p lepton, b->c-> l⁺
- soft π b->c{D*⁺->D⁰π⁺}

* multidimensional likelihood, ε>99%

Significance of CP asymmetry depends on

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



Δz: vertex reconstruction

Constrained to measured IP in r-ϕ

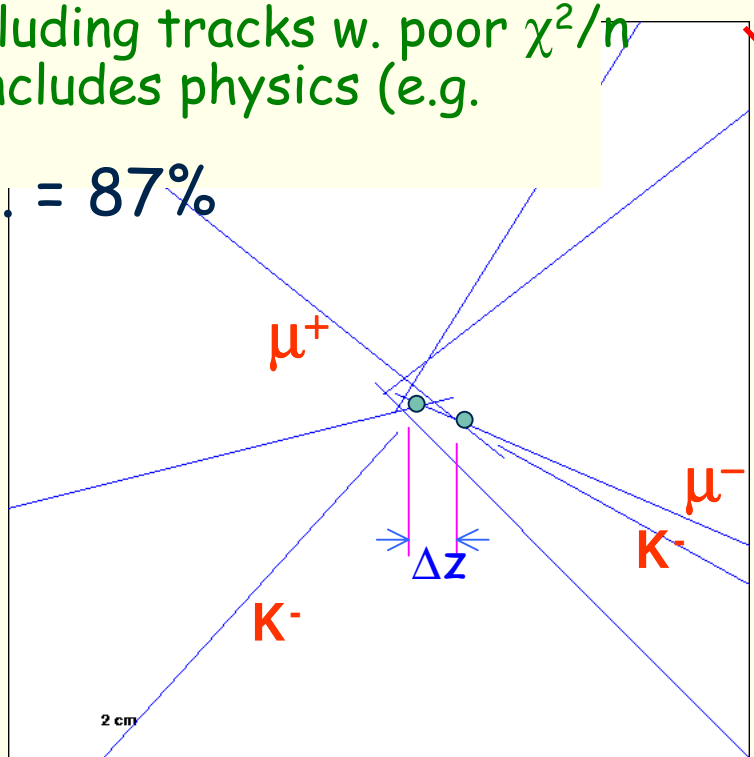
- B_{CP}: σ_z~75 μm (rms)

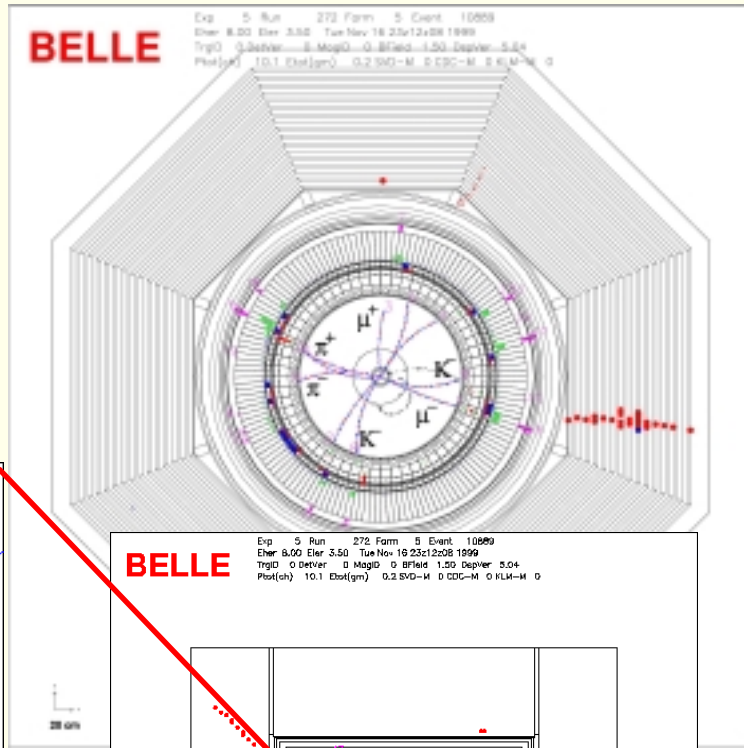
  use only tracks from J/ψ□□η□

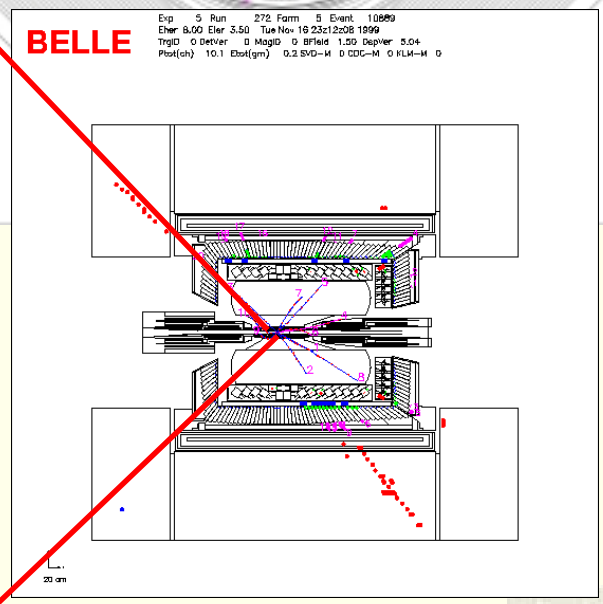
- B_{tag}: σ_z~140 μm (rms)

  remaining tracks, excluding K_s;
  iterate, excluding tracks w. poor χ^2/n
  resolution includes physics (e.g. charm)

- Overall eff. = 87%

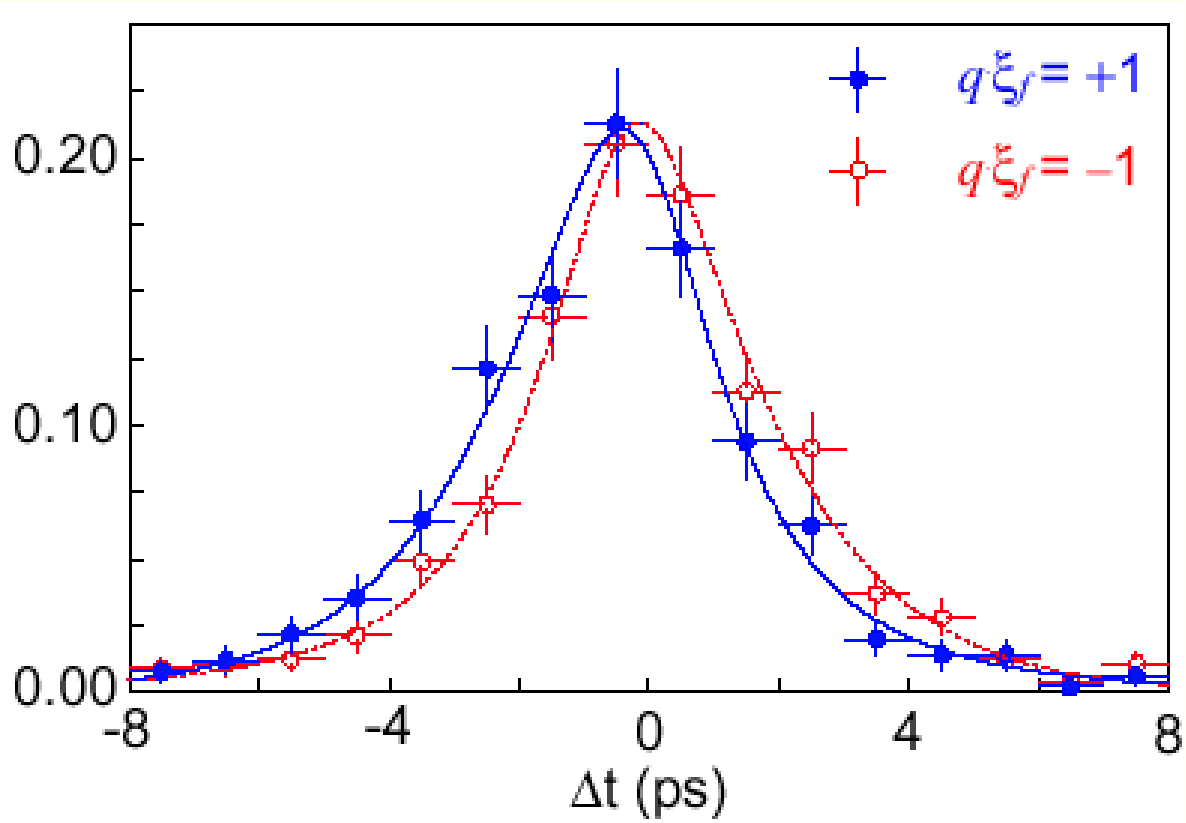






Raw Δt distributions

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±10 μm
  mixing Δm = 0.47±0.02 ps^{-1}; cT~4.0 mm
  only ~ 1 cycle of oscillation measurable

} multiply by $\beta\gamma$=0.425 for lab length (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

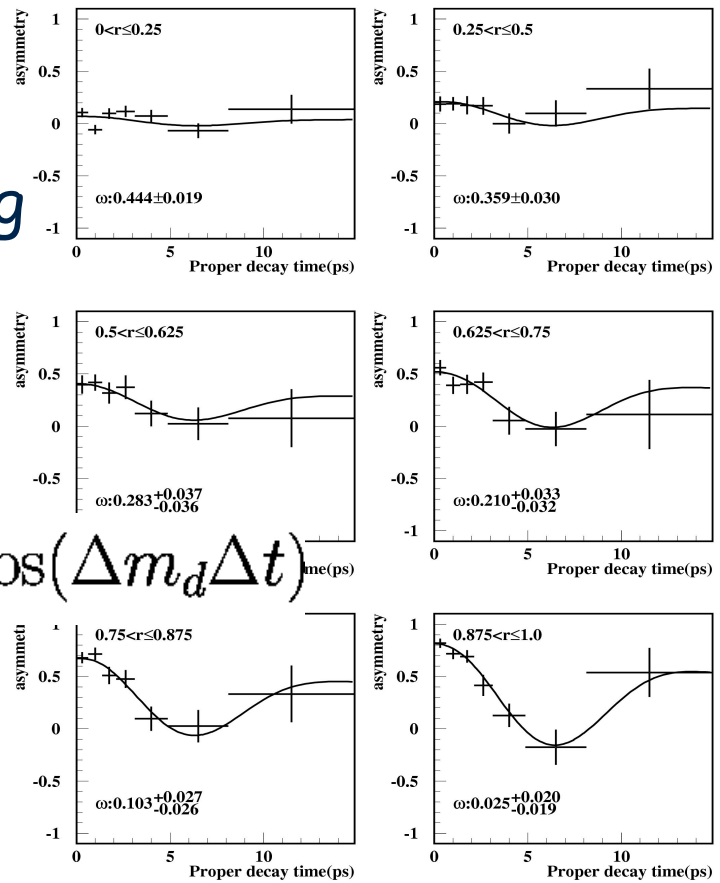
- $B \to \{D^{*-} l^+ \nu,\ D^{(*)-}\pi^+,\ D^{*-}\rho^+\}$+flavor tag
- separate same-, opp-flavor events
- fit to Δz: mixing asymmetry, w:

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

$\varepsilon_{eff} = \Sigma(1-2w_l)^2 \varepsilon_{tag,\,l} = (27.0 \pm 2.2)\%$

99.4% of candidates tagged

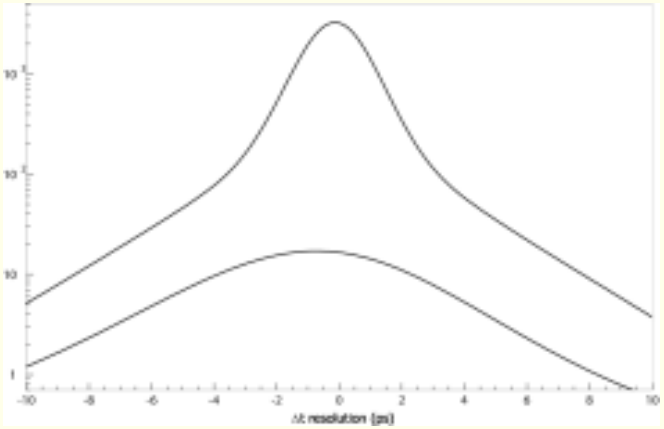
(good agreement w MC)



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 $D^0 \to K^- \pi^+$, $B \to D^* l \nu$ lifetimes
- validate: B lifetime, same fitting



tail fraction: 1.8%

$\tau_0 = 1.55 \pm 0.02$ ps (PDG2000: 1.548 ± 0.032 ps)

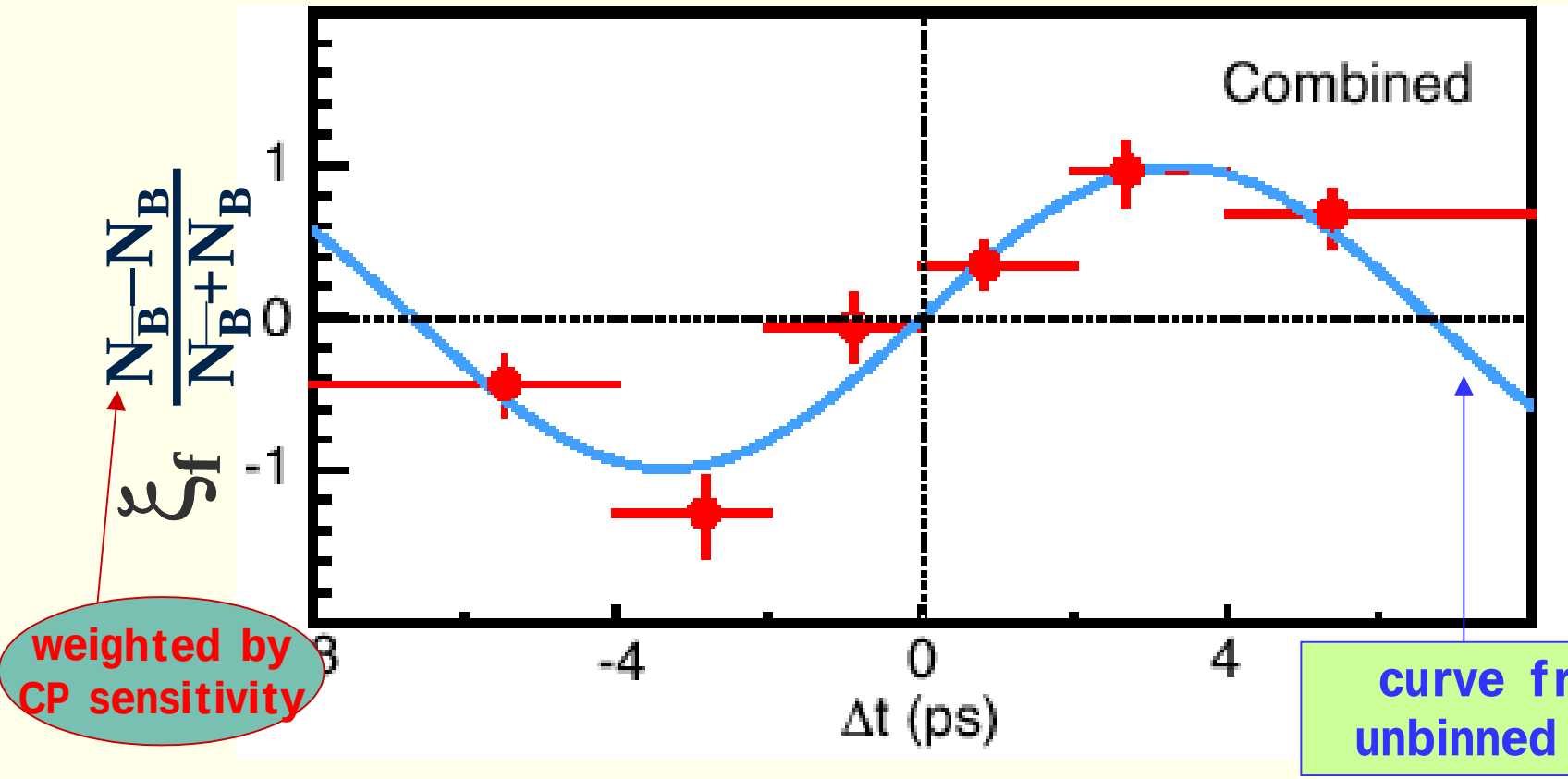
$\tau_+ = 1.64 \pm 0.03$ ps (PDG2000: 1.653 ± 0.028 ps)

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)

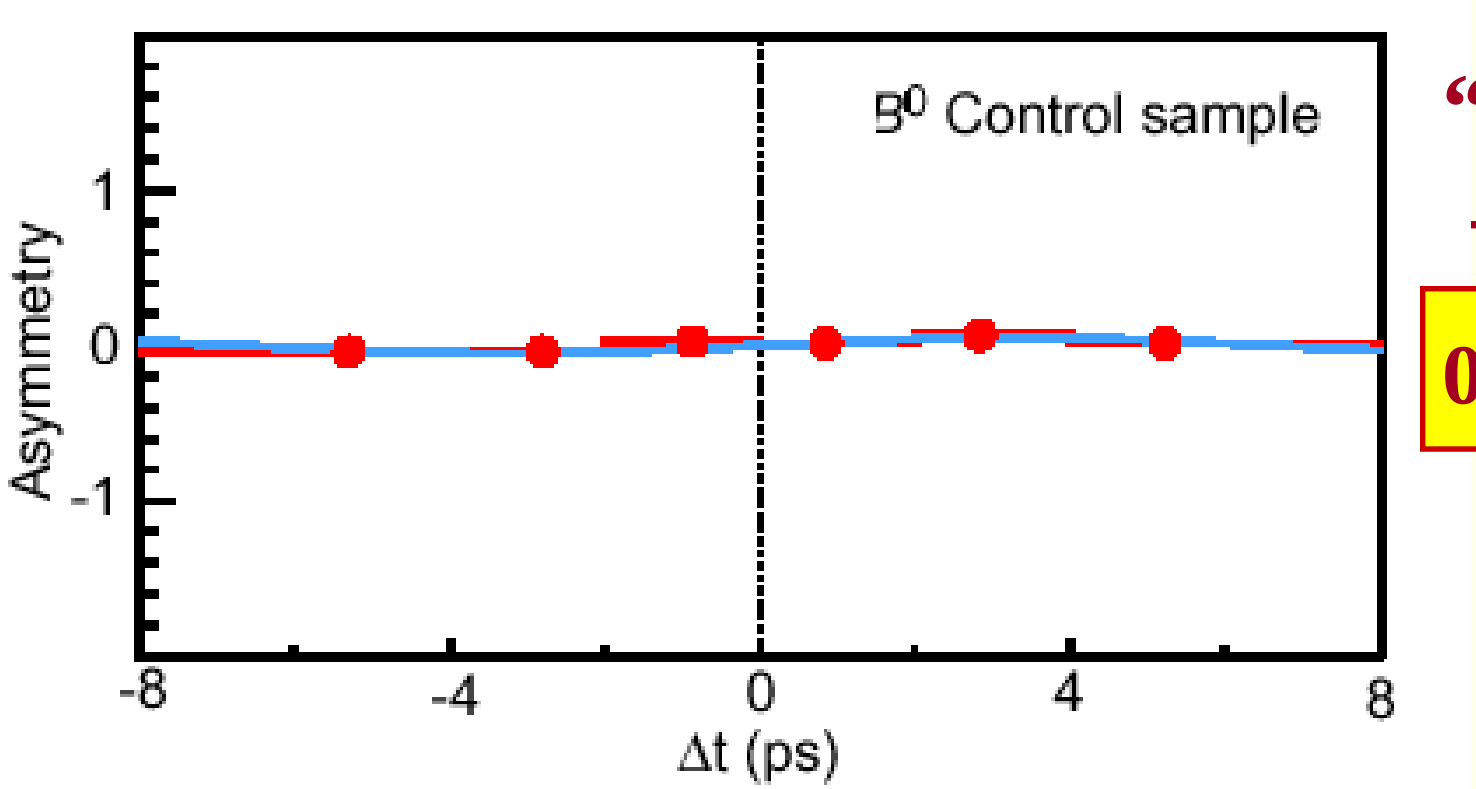
Results

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



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

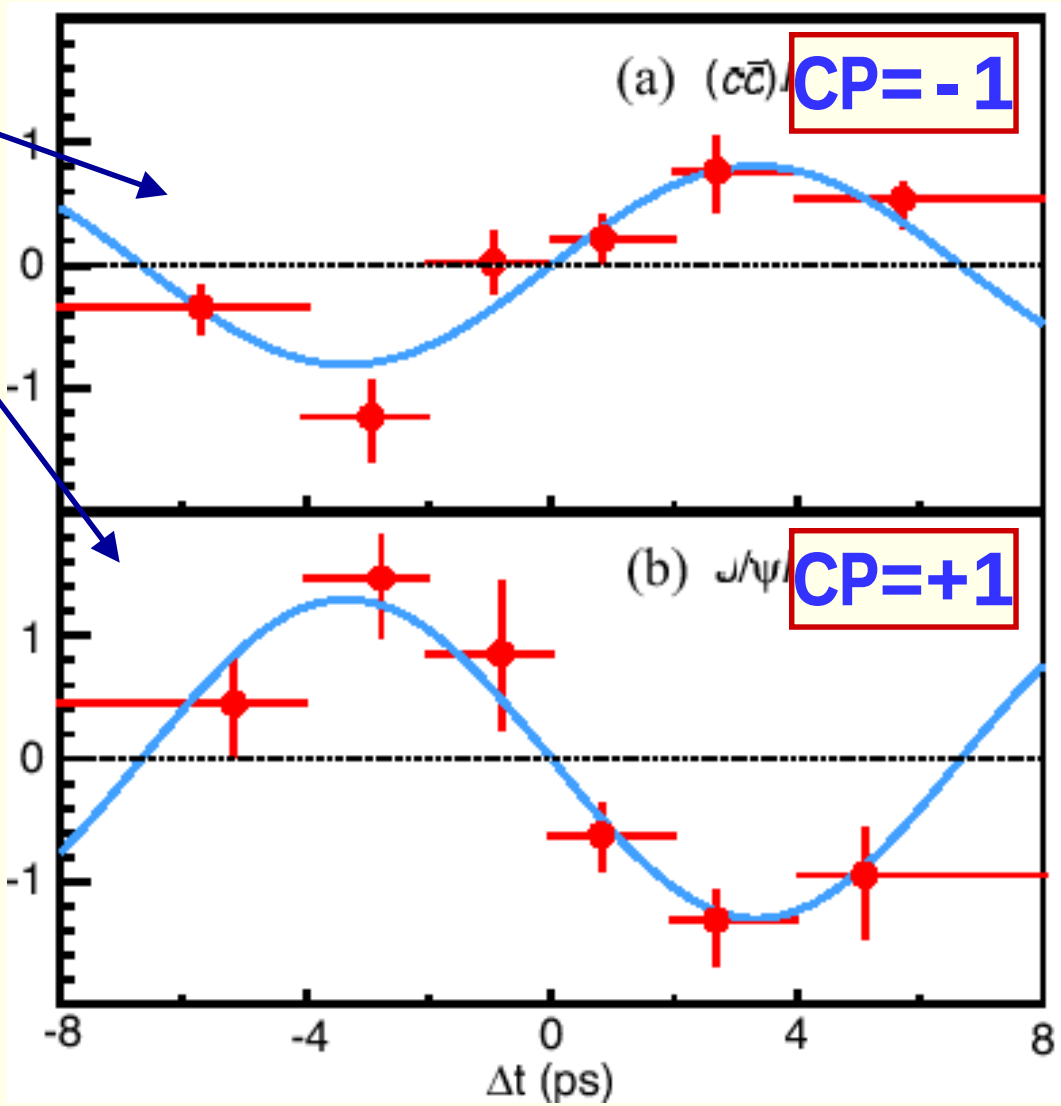
(statistical error only)

fit CP –1 and CP+1 separately:

opposite!!

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

weighted by CP sensitivity



$\sin 2\phi_1$

0.84±0.17

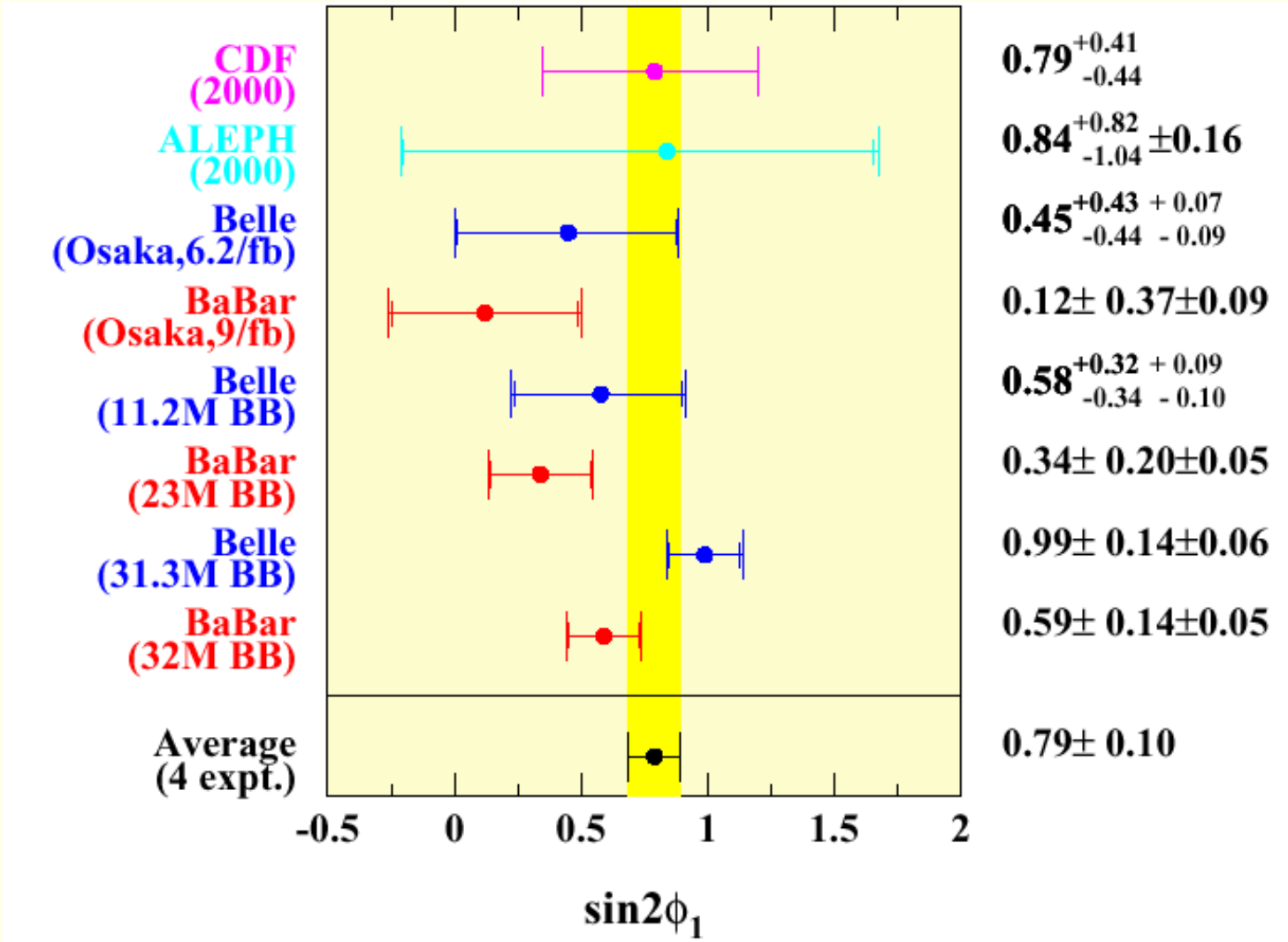
1.31±0.23

(statistical errors only)

Systematic errors

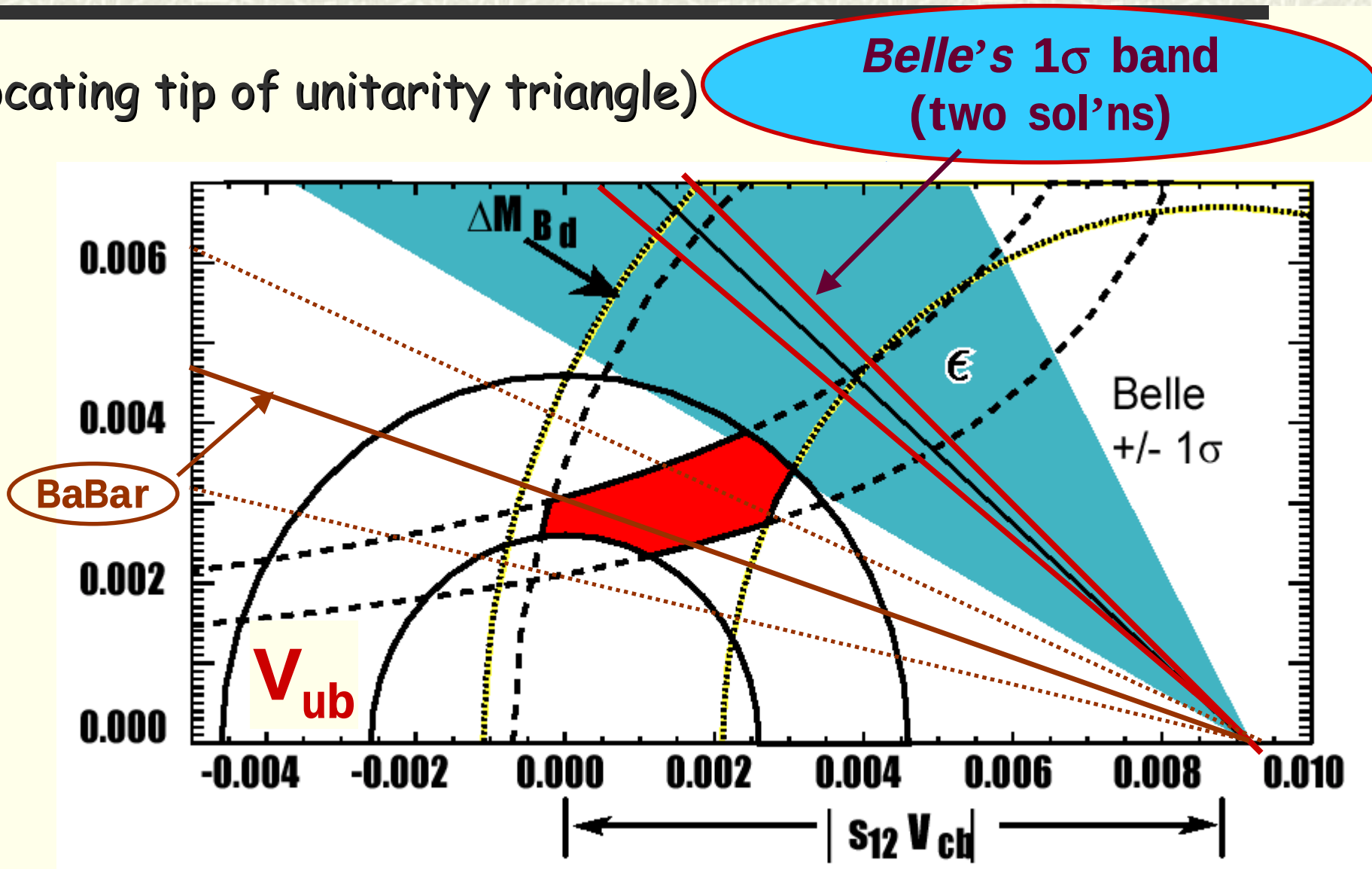
Vertex algorithm	± 0.04
Flavor tagging	± 0.03
Resolution function	± 0.02
K_L background fraction	± 0.02
Background shapes	± 0.01
Δm_d and τ_{B0} errors	± 0.01
Total	± 0.06

Compare with other experiments



Result in context

(locating tip of unitarity triangle)



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 $5.5 \times 10^{33} cm^{-2} s^{-1}$; 24 hrs 311 pb^{-1};
  month 6120 pb^{-1}
- other angles - need >300 fb^{-1} - within sight!