CP results from Belle

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Belle Collaboration

~250 physicists, 51 institutions, many nations

Aomori University
Budker Institute of Nuclear Physics
Chiba University
Chuo University
University of Cincinnati
Frankfurt University
Gyeongsang National University
University of Hawaii
Hiroshima Institute of Technology
Hiroshima College of Maritime Tech.
IHEP, Beijing
ITEP, Moscow
Joint Crystal Collaboration Group
Kanagawa University
KEK
Korea University
Krakow Institute of Nuclear Physics
Kyoto University
University of Melbourne
Mindanao State University
Nagasaki Institute of Applied Science
Nagoya University
Nara Woman's University
National Central University
National Kaoshing University
National Lien-Ho College of Tech. and Commerce
National Taiwan University
Nihon Dental College
Niigata University
Osaka University
Osaka City University
Panjab University
Princeton University
Saga University
Seoul National University
University of Science and Tech. of China
Sugiyama Woman's College
Sungkyunkwan University
University of Sydney
Toho University
Tohoku University
Tohoku-gakuin University
University of Tokyo
Tokyo Institute of Technology
Tokyo Metropolitan University
Tokyo University of Agriculure and Technology
Toyama National College of Maritime Technology
University of Tsukuba
Utkal Univesity
Virginia Polytechnic Institute and State University
Yonsei University

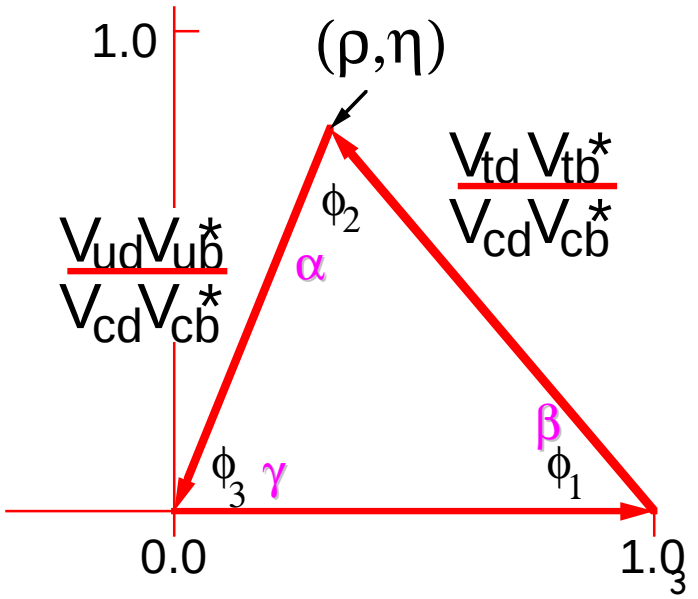
CP in the Standard Model

Unitarity of CKM:

$$\begin{array}{c} \\ u \\ c \\ t \end{array}\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix} \quad \begin{matrix} d & s & b \end{matrix}$$

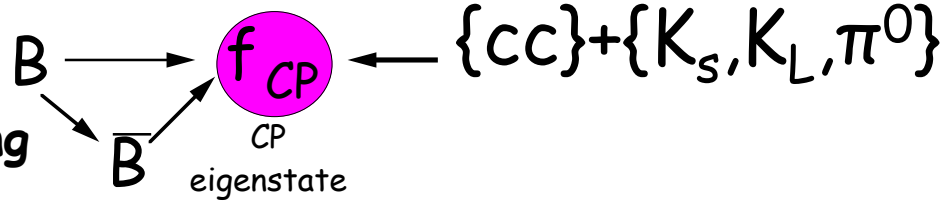
irreducibly complex
-> CP violation

$$V_{td}V_{tb}^{*}+V_{cd}V_{cb}^{*}+V_{ud}V_{ub}^{*}=0$$



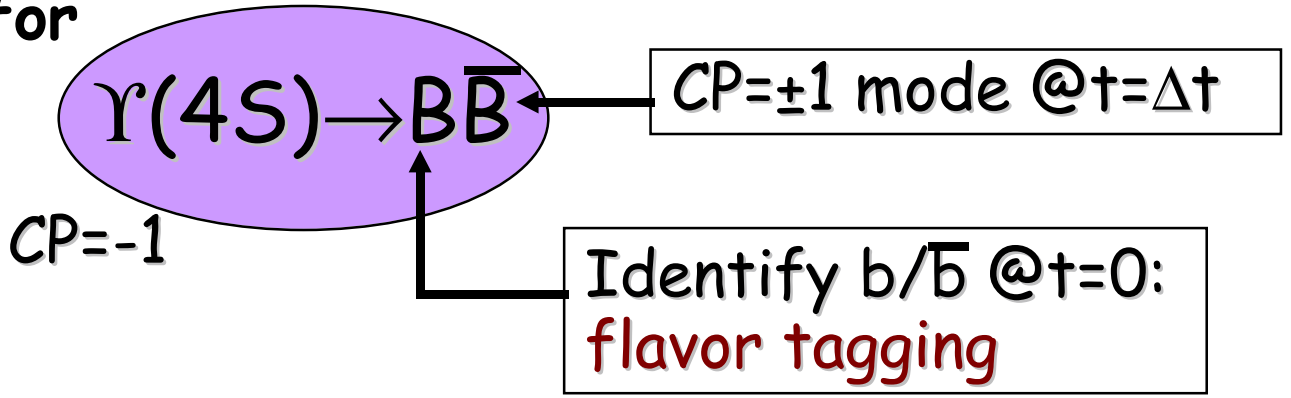
CP violation in B Decays at the $\Upsilon(4S)$

Indirect:



Interference via mixing

Such that for



Get CP-dependent oscillation in decay time difference

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

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

CP violation in B Decays at the $\Upsilon(4S)$ (cont)

Direct CP: asymmetry of B, $\bar{B}$ BR's

- $B \to D^0 K^-$, $D^0 \to K^+ K^-$ (ϕ_3)
- $B \to K\pi$, $\pi\pi$, KK (ϕ_2,ϕ_3)

These are rare decays - for CP, first need

- detection in significant numbers
- good PID to separate suppressed from unsuppressed modes

Belle detector

Charged tracking/vertexing

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

Hadron identification

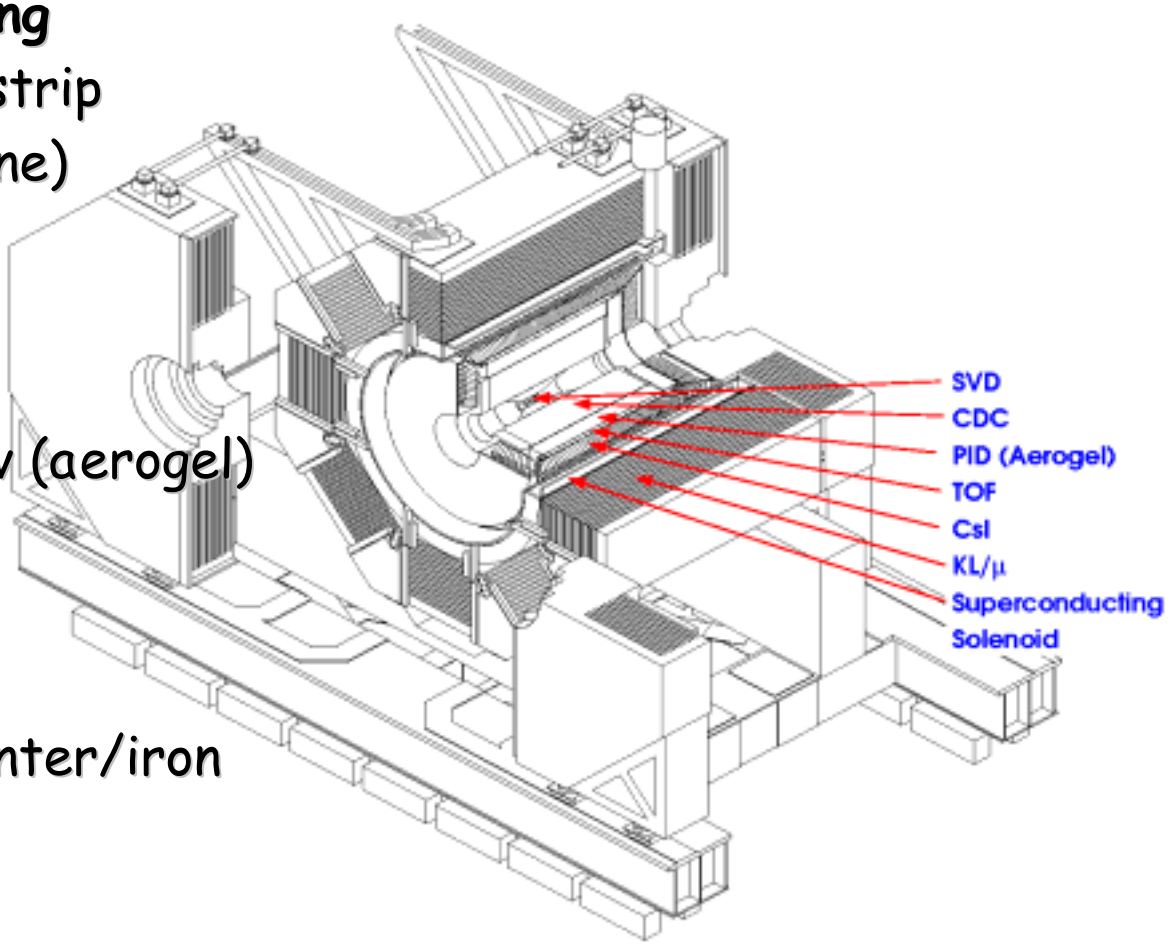
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon

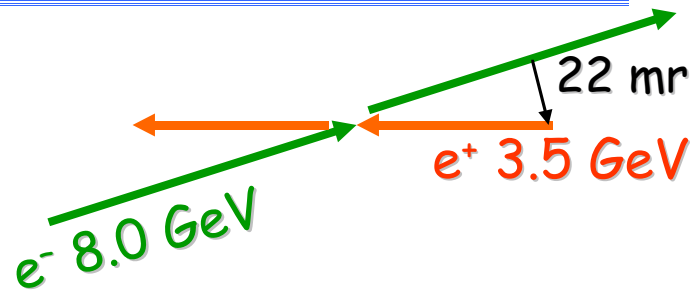
- ECL: CsI calorimeter

Muon/KL

- KLM: Resistive plate counter/iron



KEKB



$\beta\gamma = 0.425$

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

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

$\mathcal{L}_{max} = 2.0 \times 10^{33}$ cm^{-2}s^{-1} (design: 1x10^{34})

Data (6/1999-7/2000)

$\int \mathcal{L} dt = 6.2$ fb^{-1}@Υ(4S), 0.6 fb^{-1}off

$N_{BB} = 6.34 \times 10^6$ (preliminary)

Indirect CPV

Results on

- Time-dependent asymmetry

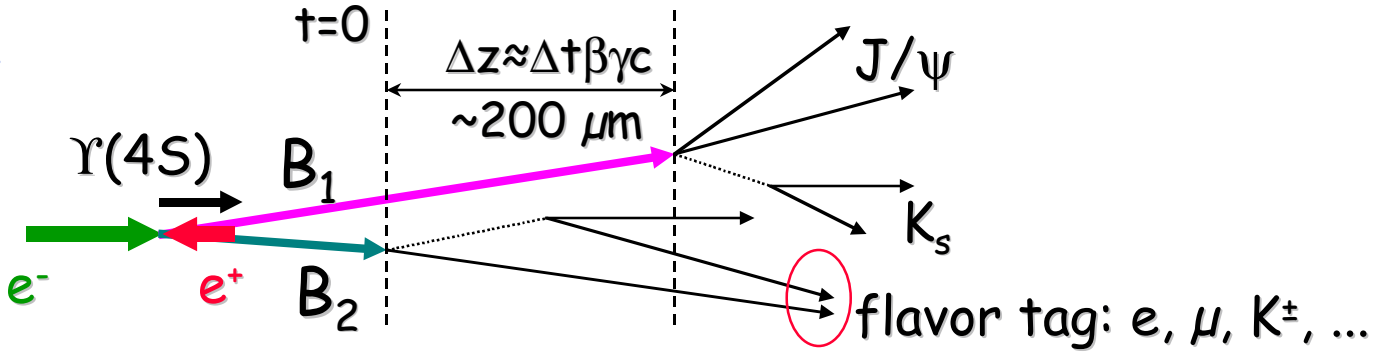
  CP tags (ϕ_1)

$J/\psi K_S$	$\psi' K_S$	$\chi_{c1}\ K_S$	$J/\psi\pi^0$	$J/\psi K_L$
$\ell^+\ell^-$	$\ell^+\ell^-$	$J/\psi\gamma$	$\ell^+\ell^-$	$\ell^+\ell^-$
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-$		
$\pi^0\pi^0$	$J/\psi\pi^+\pi^-$			

  + flavor tag (lepton, K)

- observation of $J/\psi K_1(1270)$
- polarization of $J/\psi K^*$

Concept



Experimental considerations

- True CP asymmetry (A) in signal (S) diluted by background (B), wrong flavor tag (w), vertex resolution (d_{res})
- Parametrized by dilution factor (D):

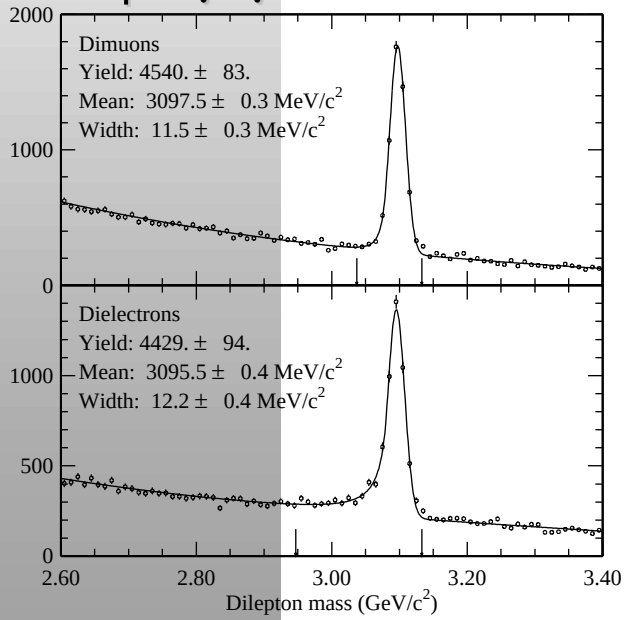
$$D = \frac{(1-2w)d_{res}}{\sqrt{1+B/S}}$$

CP modes Indirect CPV (cont)

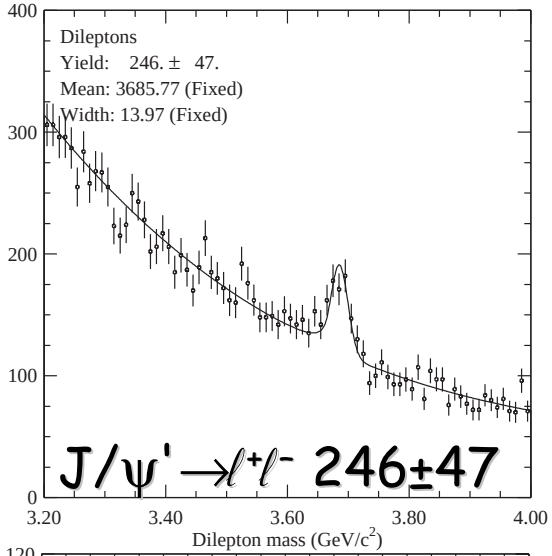
Inclusive charmonium

$\int \mathcal{L} dt = 6.2\ fb^{-1}$

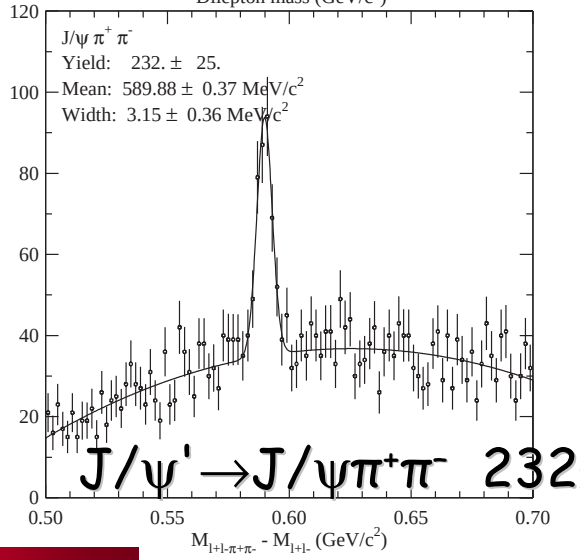
$J/\psi \to \mu^+\mu^-$ 4540±83



$J/\psi \to e^+e^-$ 4429±94



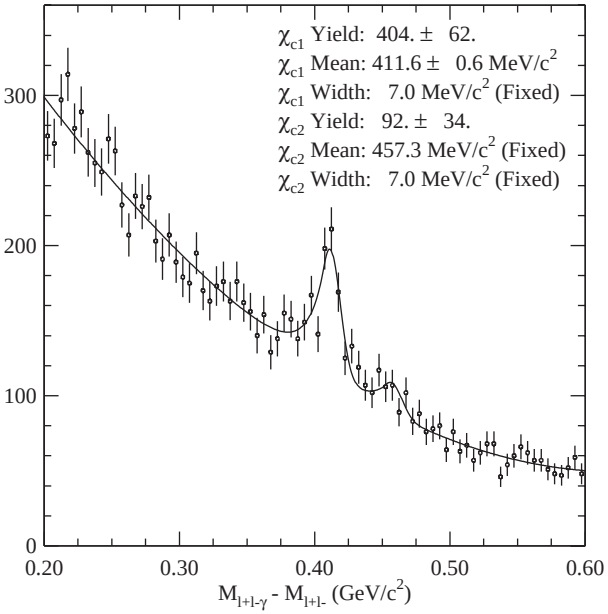
$J/\psi' \to \ell^+\ell^-$ 246±47



$J/\psi' \to J/\psi\pi^+\pi^-$ 232±25

PRELIMINARY

$\chi_{c1} \to J/\psi\gamma$ 404±62



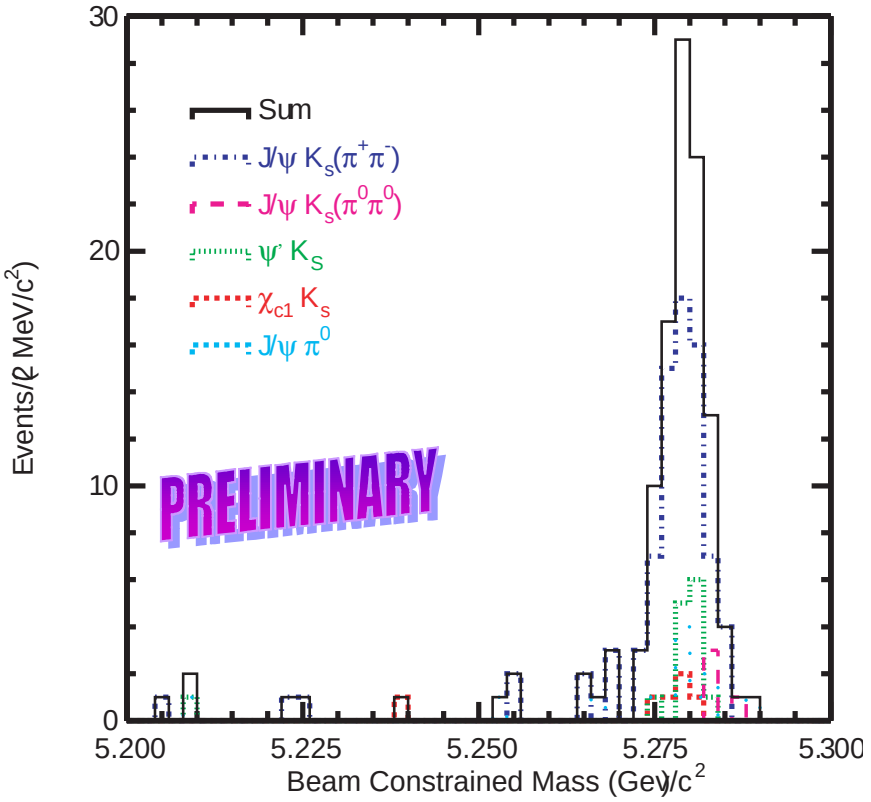
Exclusive $\{c\bar{c}\}K_s$ Indirect CPV (cont)

Energy $E^*_{cand}-E^*_{beam}\equiv\Delta E=0\pm(10\text{-}50\ MeV)$
depends on mode ($E^*_{beam}\equiv\sqrt{s}/2$)

Beam-constrained mass

$$M_B\equiv\sqrt{E^*_{beam}{}^2-p^*_{cand}{}^2}$$

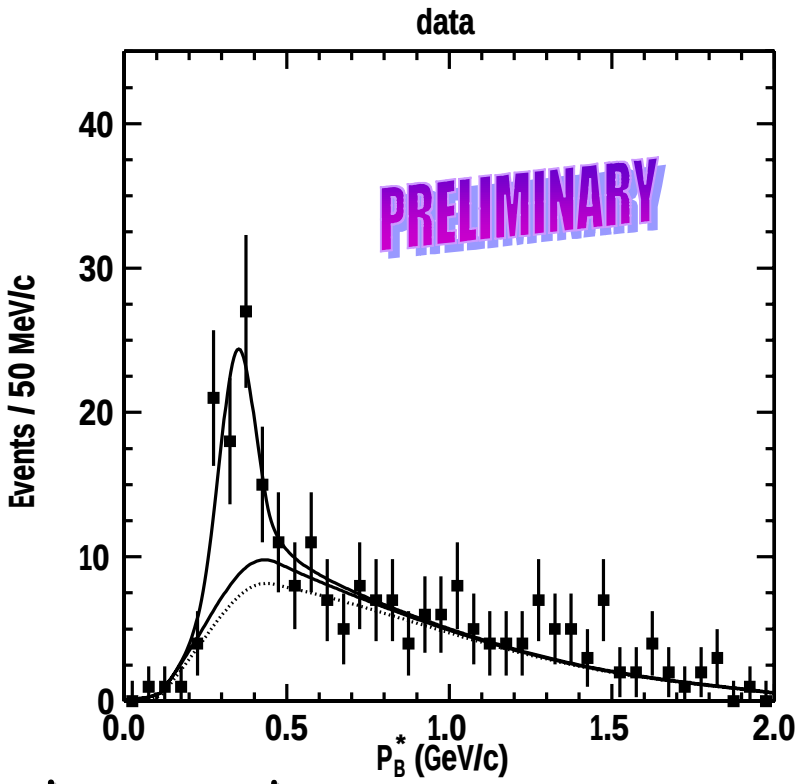
- Cut on ΔE, plot M_B:



$J/\psi K_L$ Indirect CPV (cont)

Candidates

- J/ψ: tighter cuts than ψK_s,
  $1.42<p^*<2.00$ GeV/c
- K_L within 45° of expected lab direction
- Calculate momentum in CMS (p^*) of B cand, (assume B at rest in CMS)
- fit to signal+bg



Backgrounds

- Mainly "physics":
  $J/\psi K^*$, ...
- shapes estimated via MC

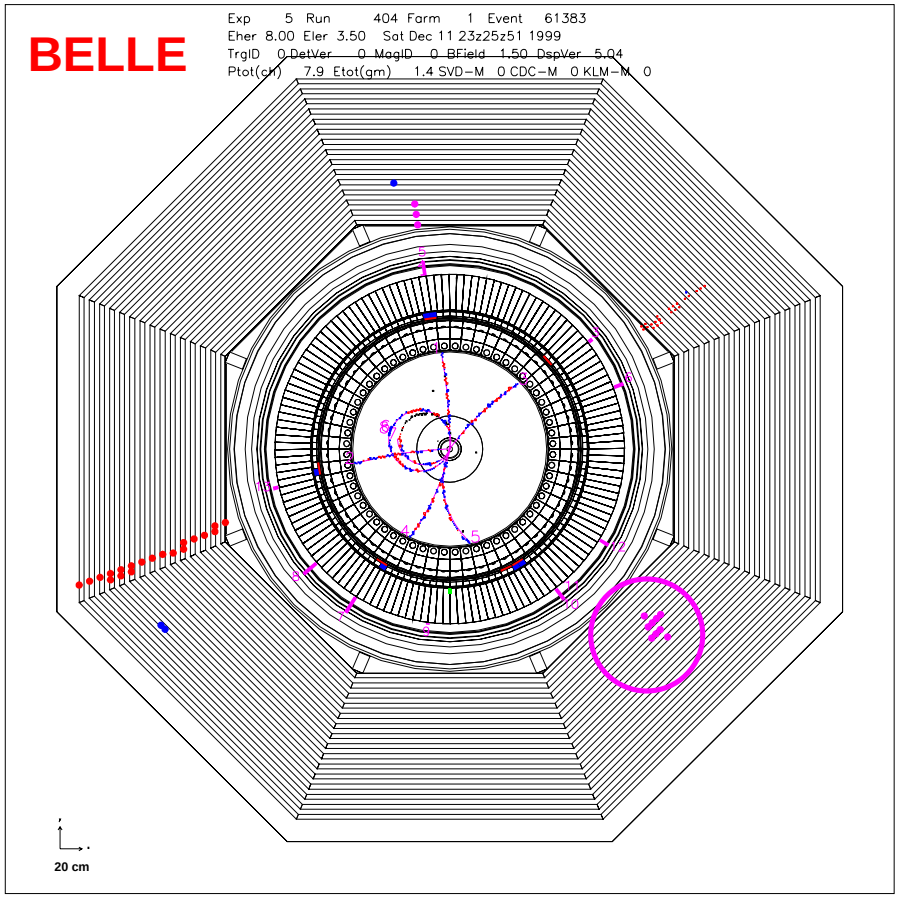
ψK_L Indirect CPV (cont)

K_L:

KLM/ECL clusters w/o track

>1 KLM superlayers

Angular resolution: 3° (1.5° if ECL hit)

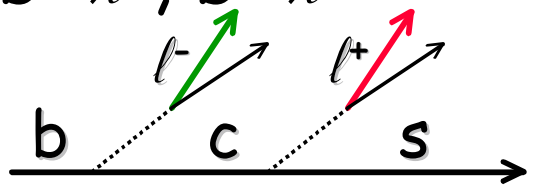


Flavor tagging

Indirect CPV (cont)

Flavor of other B by tagging

- high-p lepton ($p^*>1.1$ GeV): $b\to\ell^-$, $\bar{b}\to\ell^+$
- net K charge: $b\to K^-$, $\bar{b}\to K^+$
- (medium-p lepton, soft π)



Significance of CP asymmetry depends on

- tagging efficiency
- wrong-tag fraction w (measured)

Tagging summary

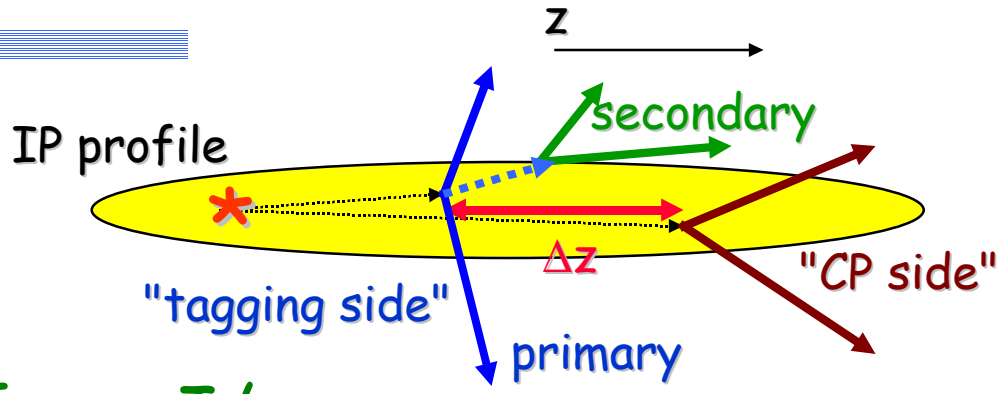
Indirect CPV (cont)

$\int \mathcal{L} dt = 6.2\ fb^{-1}$

PRELIMINARY

	Decay mode	# cands	est. bg	# tagged
CP=-1	$J/\psi K_s$, $K_s \to \pi^+\pi^-$	70	3.4±1.0	40
	$J/\psi K_s$, $K_s \to \pi^0\pi^0$	4	0.3±0.1	4
	$\psi(2S)K_s$, $\psi(2S) \to l^+l^-$	5	0.2±0.1	2
	$\psi(2S)K_s$, $\psi(2S) \to J/\psi\pi^+\pi^-$	8	0.6±0.3	3
	$\chi_{c1}K_s$	5	0.8±0.4	3
CP=+1	$J/\psi K_L$	102	47.6±4.8	42
	$J/\psi\pi^0$	10	0.6±0.3	4
	Total	204		98

Measuring and fitting Δz Indirect CPV (cont)



z vertices

- B_{CP}: σ_z~40 μm
  use only leptons from J/ψ
  constrained fit to measured IP
- B_{tag}: σ_z~85 μm
  remaining tracks, excluding K_s;
  iterate, excluding tracks w. poor χ^2/n
  resolution includes physics (e.g. charm)
- $\sigma_{\Delta z}$~100 μm (MC)

Measuring and fitting Δz (cont)

Fitting

- 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 resolution (parametrized,evt-by-evt)

Wrong tag fraction Measuring/fitting Δz (cont)

Same fit method, but flavor-specific mode

- $B \to D^{*-} \ell^+ \nu$, $D^- \ell^+ \nu$ + flavor tag (2 separate)
- separate same-, opp-flavor events
- fit to Δz: outputs - wrong tag fraction for $B^0(w)$, $B^-(w^+)$, mixing (Δm_d), resolution function

Asymmetry due to mixing

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

"effective tagging efficiency" $\varepsilon_{eff} = (1-2w)^2 \varepsilon_{tag}$

Wrong tag fraction Measuring/fitting Δz (cont)

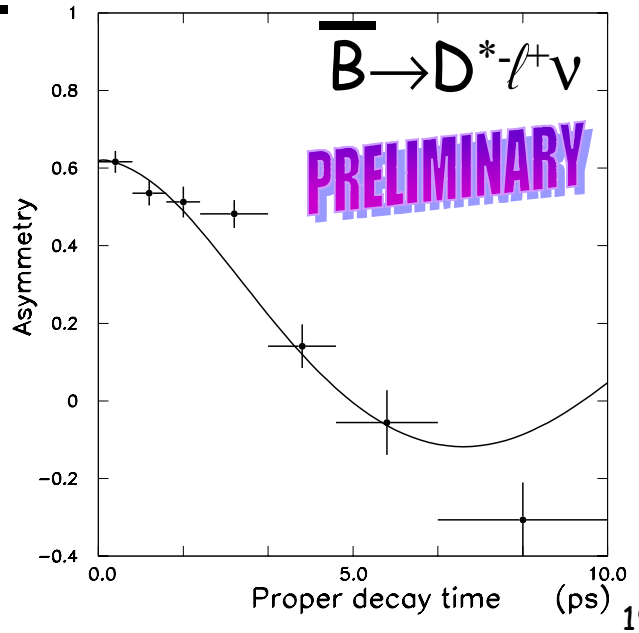
Tag	ε_{tag}(%)	w(%)	ε_{eff}(%)
high-p* lepton	14.2±2.1	7.1±4.5	10.5±2.7
Kaon	27.9±4.2	19.9±7.0	10.1±4.9
med-p* lepton	2.9±1.5	29.2±15.0	0.5
soft π	7.0±3.5	34.1±15.0	0.7
Total	52.0		21.2

MC values

$\int \mathcal{L} dt = 5.1\ fb^{-1}$

$\Delta m_d = 0.49 \pm 0.026\ ps^{-1}$

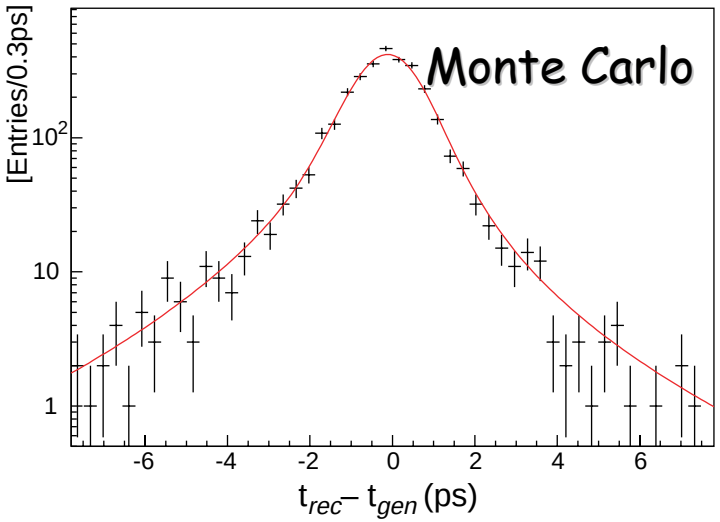
(PDG: 0.472±0.017 ps^{-1})



Δt resolution Measuring and fitting Δz (cont)

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, params determined by
  - Monte Carlo
  - fits for $D^0 \to K^-\pi^+$, $B \to D^*\ell\nu$ lifetimes



Δt resolution Measuring and fitting Δz (cont)

Δt used in other measurements, serve as checks

- B^0 mixing w. dileptons

PRELIMINARY $\Delta m_d = 0.456 \pm 0.008 \pm 0.030$ ps^{-1}

(PDG2000: 0.472 ± 0.017 ps^{-1})

$\int \mathcal{L} dt = 5.1$ fb^{-1}

- B lifetimes

  Reconstructed B + flavor tag vertex

  $B \rightarrow DX$ semileptonic+hadronic, ψX modes.

PRELIMINARY $\tau_0 = 1.50 \pm 0.05 \pm 0.07$ ps

(PDG2000: 1.548 ± 0.032 ps)

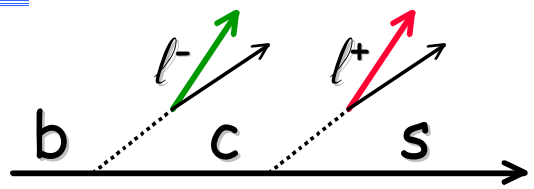
$\int \mathcal{L} dt = 5.1$ fb^{-1}

PRELIMINARY $\tau_+ = 1.70 \pm 0.06 \pm 0.11$ ps

(PDG2000: 1.653 ± 0.028 ps)

Δt resolution Measuring and fitting Δz (cont)

B^0 mixing w. dileptons



Same sign

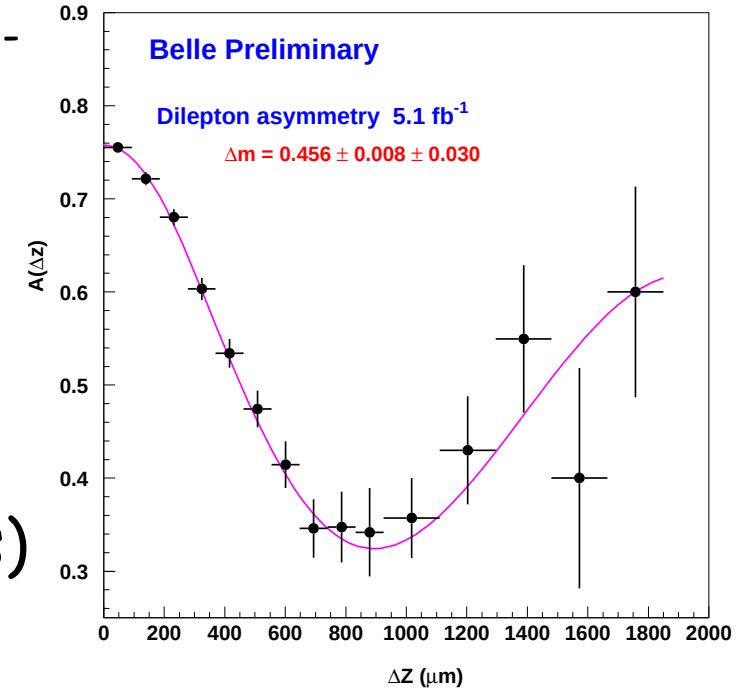
- 2 primaries, mixed event
- Primary+2ndary, unmixed & B^+B^-
- Backgrounds

Opposite sign

- 2 primaries, unmixed & B^+B^-
- Primary+2ndary, mixed&unmixed
- Backgrounds

Asymmetry in signal (2 primaries)

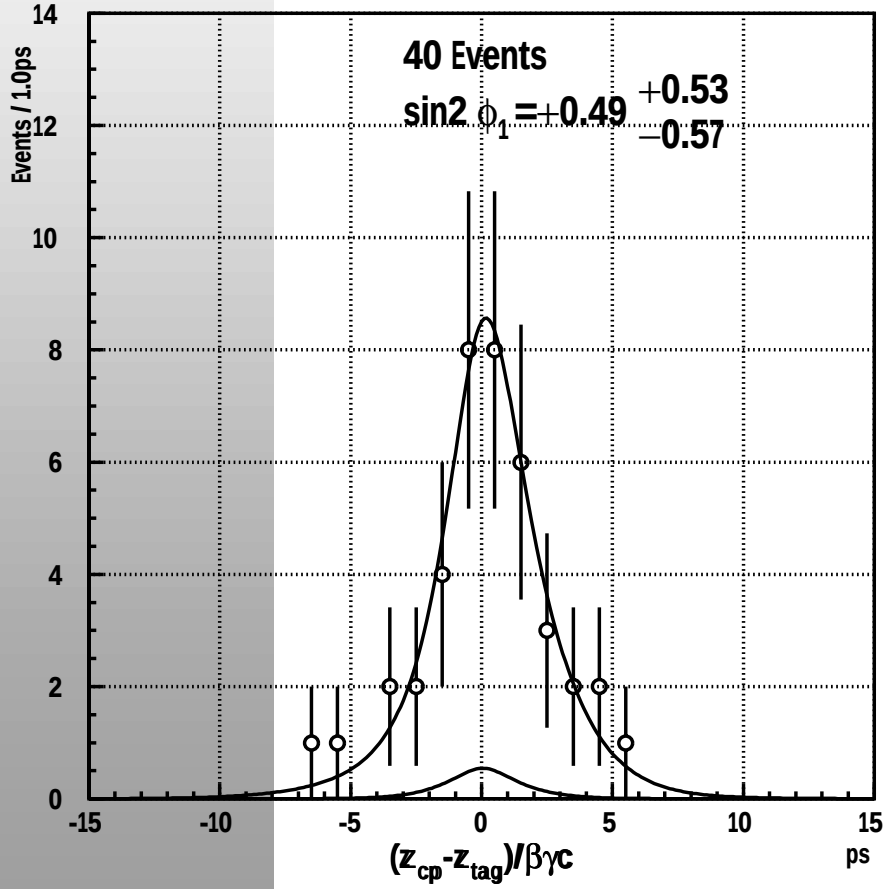
$$\frac{N_{opp}-N_{same}}{N_{opp}+N_{same}}$$



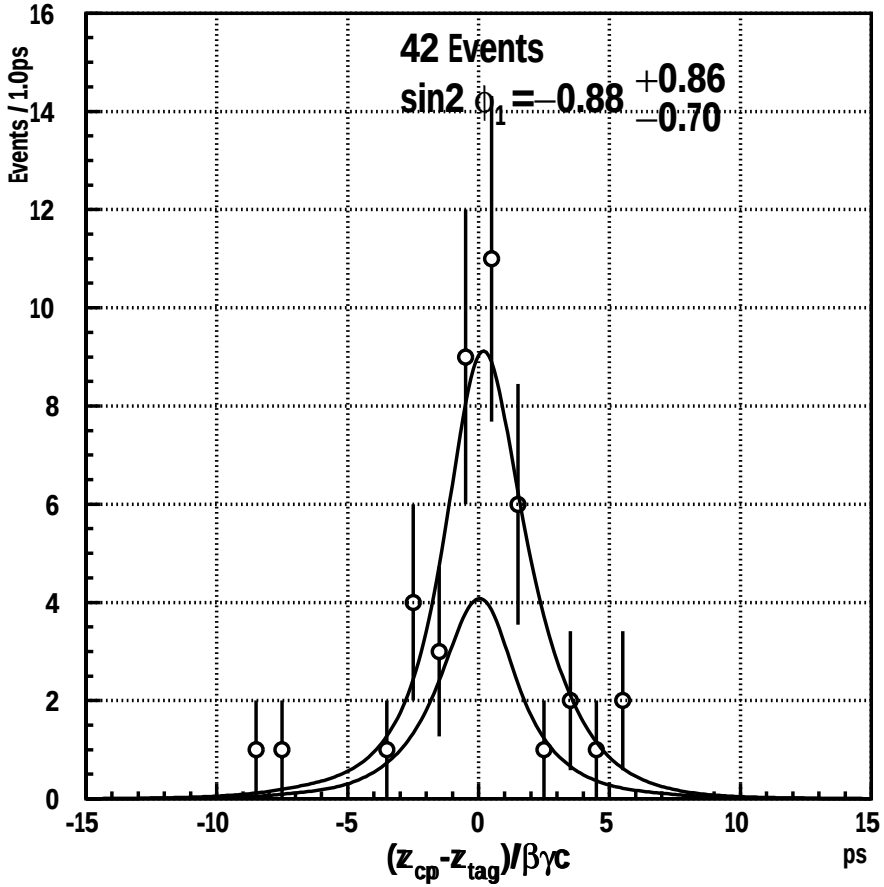
Results Indirect CPV (cont)

PRELIMINARY

$J/\psi K_s$

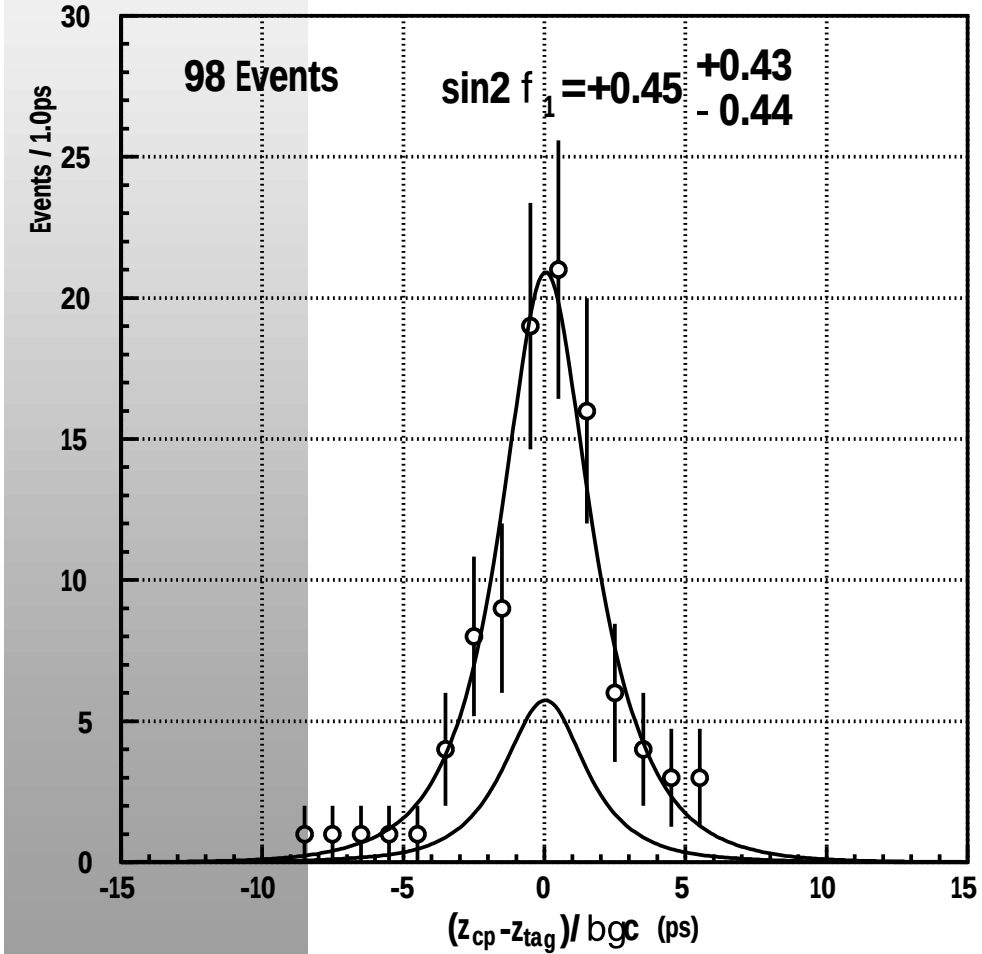


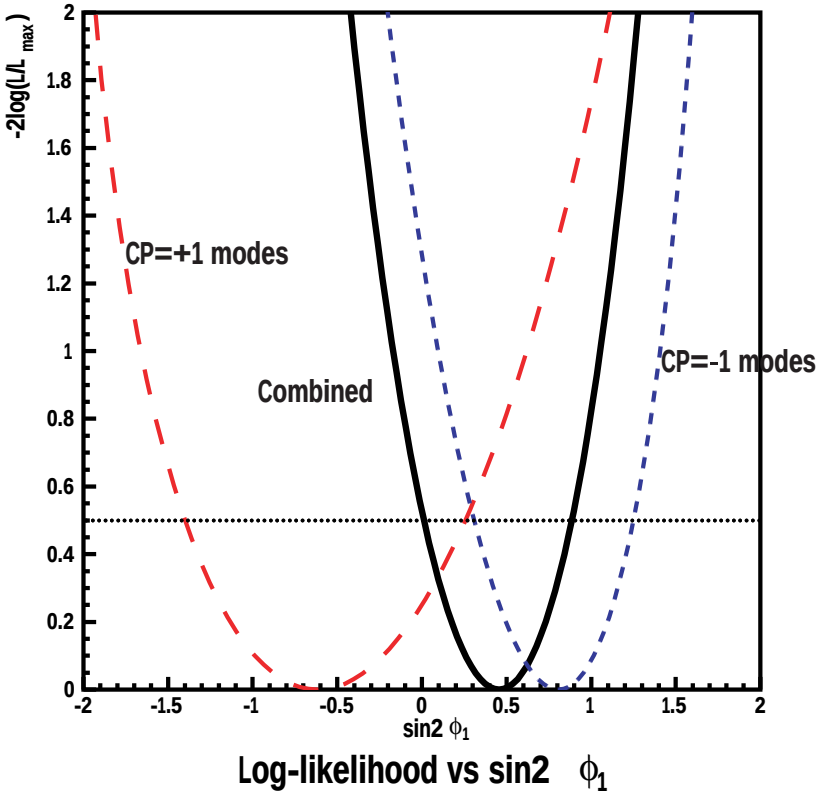
$J/\psi K_L$



Results Indirect CPV (cont)

Combined fit, CP=±1





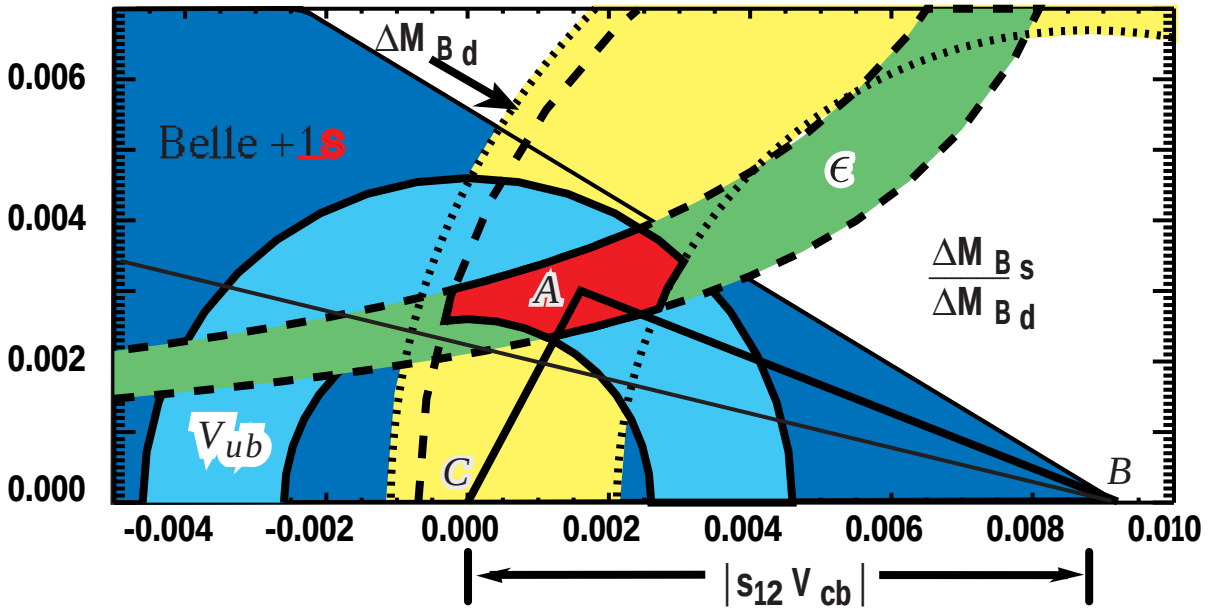
Log-likelihood vs sin2 ϕ_1

PRELIMINARY

$$\sin 2\phi_1 = 0.45\ ^{+0.43+0.07}_{-0.44-0.09}$$

$\int \mathcal{L} dt = 6.2\ fb^{-1}$

Constraints on unitarity? Indirect CPV (cont)



Not quite, but...

- still developing additional modes, tagging methods
- expect much more $\int \mathcal{L} dt$ in the next year

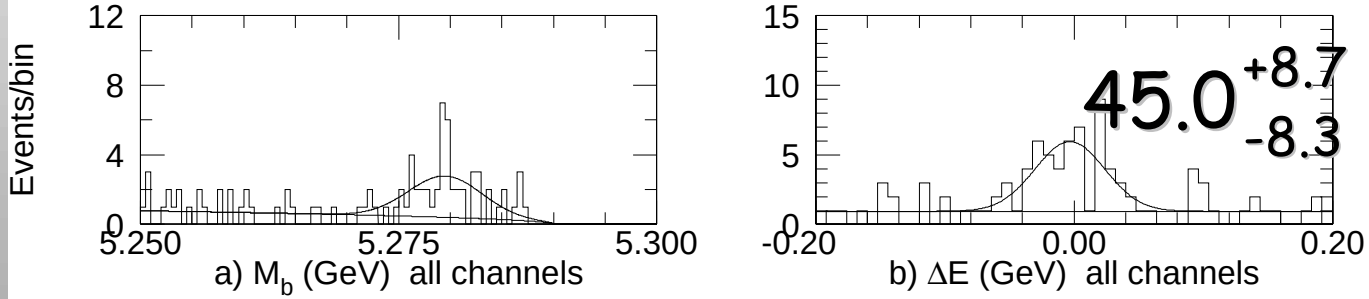
Observation of $J/\psi K_1(1270)$ Indirect CPV (cont)

CP eigenstate when $K_1^0 \to K_s \rho^0$

$J/\psi \to e^+e^-, \mu^+\mu^-$ $\int \mathcal{L} dt = 5.3\ fb^{-1}$

$+ K_1(1270) \to K\rho \to K^+\pi^+\pi^-, K^+\pi^-\pi^0, K^0\pi^+\pi^-$

$(0.62 < M_{\pi\pi} < 0.84\ GeV/c^2,\ M_{K\pi\pi} < 1.38\ GeV/c^2)$



Measure ratios w. $B^+ \to J/\psi K^+$ ($B=(9.9\pm1.0)\times10^{-4}$):

PRELIMINARY

$B(B^0 \to J/\psi K_1^0(1270)) = (1.4\pm0.4\pm0.4)\times10^{-3}$

$B(B^+ \to J/\psi K_1^+(1270)) = (1.5\pm0.4\pm0.4)\times10^{-3}$

Polarization of $J/\psi K^*$ Indirect CPV (cont)

If helicity = $|0,0\rangle$, $CP=+1$ for $B^0 \to J/\psi K^*$, $K^{*0} \to K_s \pi^0$

Reconstruct w. $J/\psi \to \ell^+\ell^-$, $K^* \to K^+\pi^-$, $K_s\pi^+$, $K^+\pi^0$

176 candidates, fit decay angle distributions

$\int \mathcal{L} dt = 5.1\ fb^{-1}$

- Helicity

  $\to \Gamma_L/\Gamma = 0.52 \pm 0.06 \pm 0.04$

- Transversity

  $\to |A_\perp|^2 = 0.27 \pm 0.11 \pm 0.05$

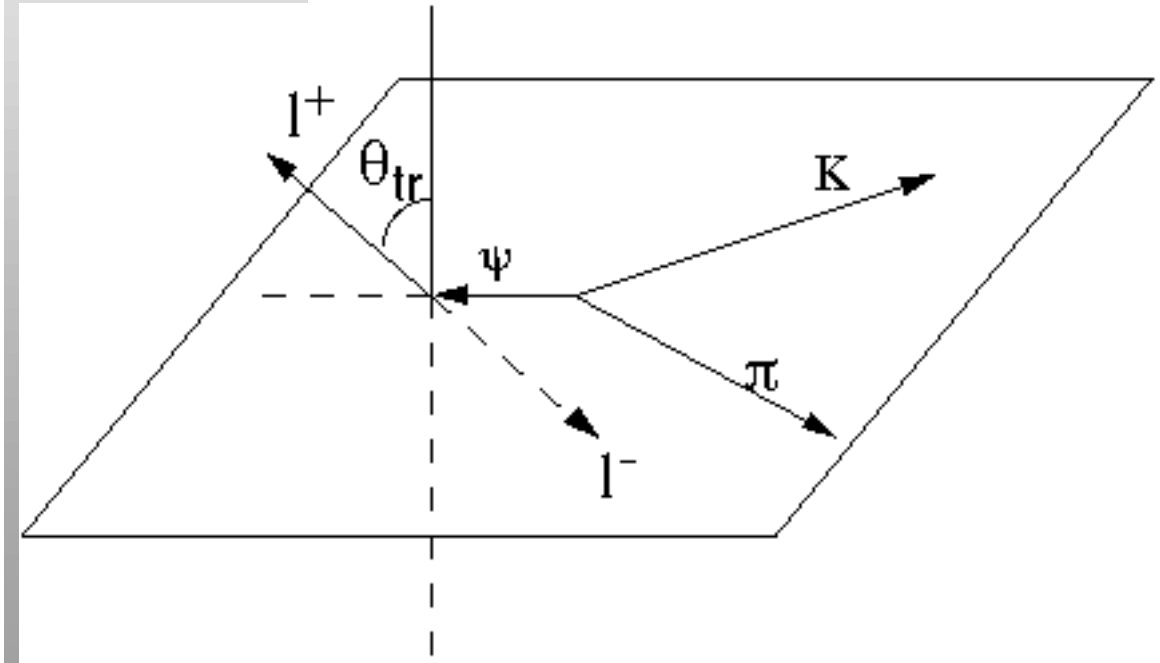
PRELIMINARY

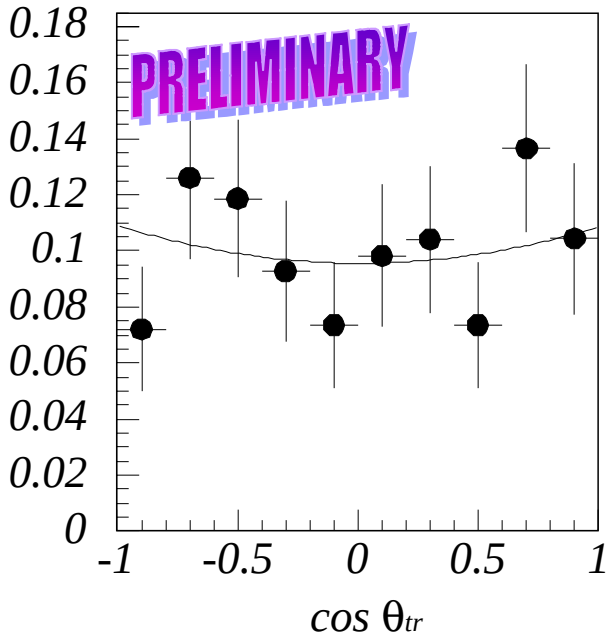
Conclude: $CP=+1$ dominates

Polarization of $J/\psi K^*$

Transversity

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{tr}} = \frac{3}{8}(1+\cos^2\theta_{tr})(1-|A_\perp|^2) + \frac{3}{4}|A_\perp|^2\sin^2\theta_{tr}$$



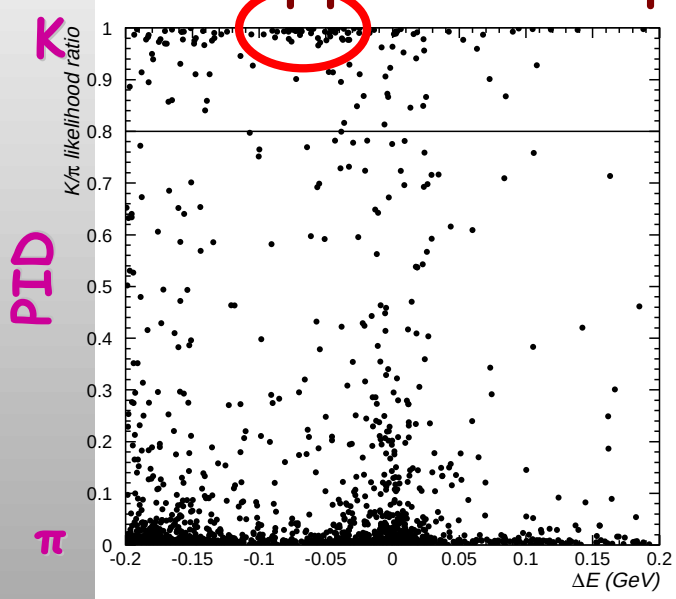


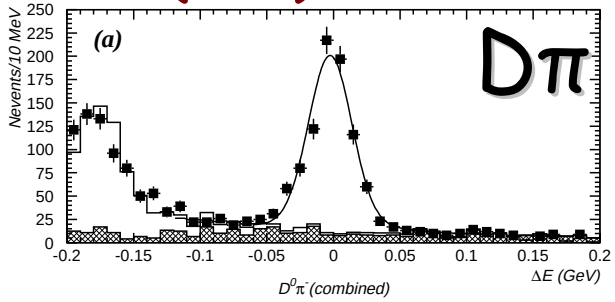
Direct CP modes: $B \to D^{(*)}K$

$\int \mathcal{L} dt = 5.3\ fb^{-1}$

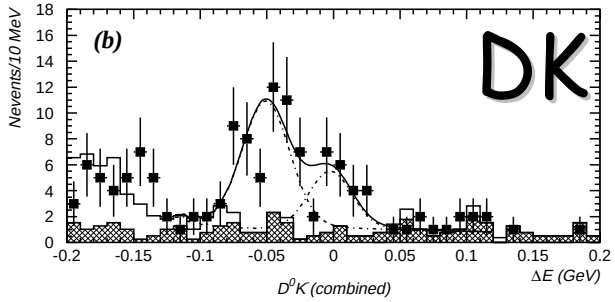
$B \to D^0 K^-$ $\{D^0 \to f_{CP}\}$ sensitive to ϕ_3

CKM-suppressed: plot $\Delta E(D\pi)$ vs PID





PID<0.8



PID>0.8

PRELIMINARY

$\mathcal{B}(B^- \to D^0 K^-)/\mathcal{B}(B^- \to D^0 \pi^-) = 0.081 \pm 0.014 \pm 0.011$

$\mathcal{B}(B^- \to D^{*0} K^-)/\mathcal{B}(B^- \to D^{*0} \pi^-) = 0.134^{+0.045}_{-0.036} \pm 0.015$

$\mathcal{B}(B^- \to D^{*+} K^-)/\mathcal{B}(B^- \to D^{*+} \pi^-) = 0.062^{\pm 0.030}_{-0.024} \pm 0.013$

Direct CP modes: $B \to K\pi, \pi\pi$

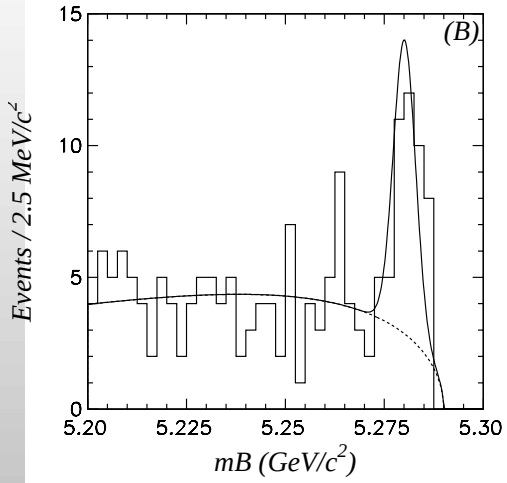
Penguins, CPV, new physics, ...

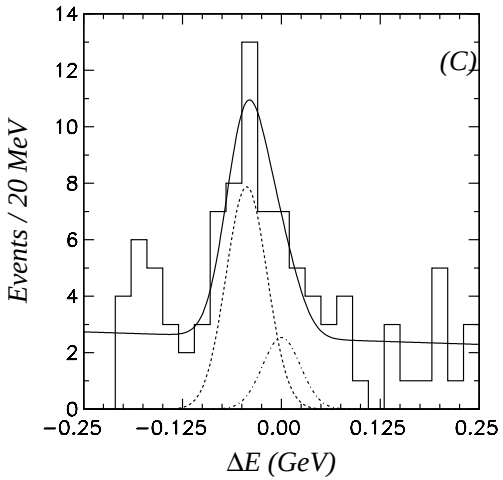
PRELIMINARY

Mode	Yield	Signifi-cance	ε	BRx10^5	ULx10^5 (90%CL)
$K^+\pi^-$	$25.6^{+7.5}_{-6.8}\pm3.8$	4.4	0.28±0.04	$1.74^{+0.51}_{-0.46}\pm0.34$	-
$\pi^+\pi^-$	$9.3^{+5.7}_{-5.1}\pm2$	1.9	0.28±0.04	$0.63^{+0.39}_{-0.35}\pm0.16$	1.65
K^+K^-	$0.8^{+2.1}_{-0.8}$	-	0.20±0.03	-	0.6
$K^0\pi^-$	$5.7^{+3.4}_{-2.7}\pm0.6$	2.4	0.13±0.02	$1.66^{+0.98}_{-0.78}\pm0.24$	3.4
K^0K^+	$0.0^{+0.5}_{-0.0}$	-	0.11±0.02	-	0.8
$K^+\pi^0$	$32.3^{+9.4}_{-8.4}{}^{+2.4}_{-2.2}$	5.0	0.31	$1.88^{+0.55}_{-0.49}\pm0.23$	-
$K^0\pi^0$	$5.4^{+5.7}_{-4.4}{}^{+1.0}_{-1.1}$	1.3	0.30	$0.33^{+0.35}_{-0.27}\pm0.07$	1.0
$\pi^+\pi^0$	$10.8^{+4.8}_{-4.0}{}^{+0.7}_{-0.5}$	3.9	0.19	$2.10^{+0.93}_{-0.78}\pm0.25$	-

Direct CP modes: B→Kπ, ππ

$K^+\pi^-$





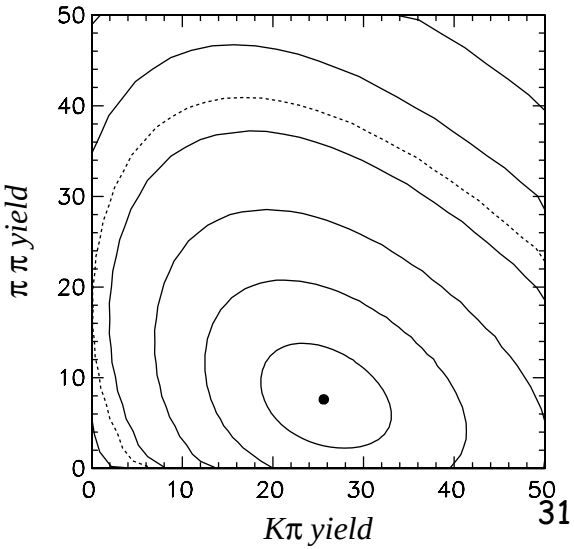
$\int \mathcal{L} dt$ = 5.1 fb^{-1}

PRELIMINARY

M_B

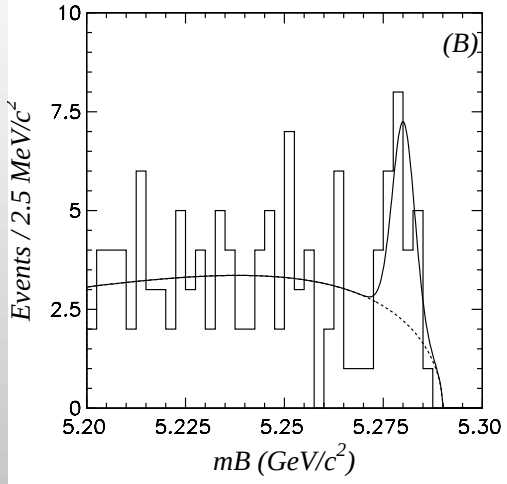
ΔE

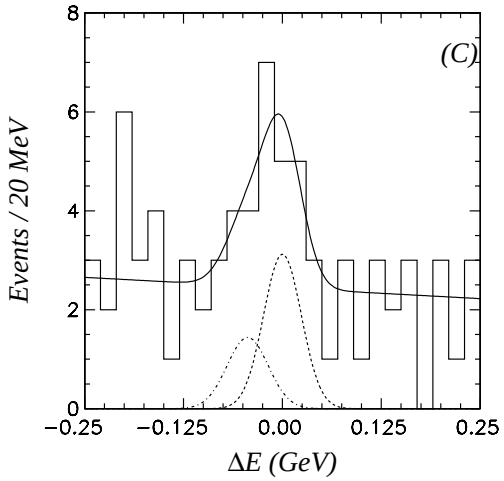
ΔE fit likelihood contours: Kπ vs ππ



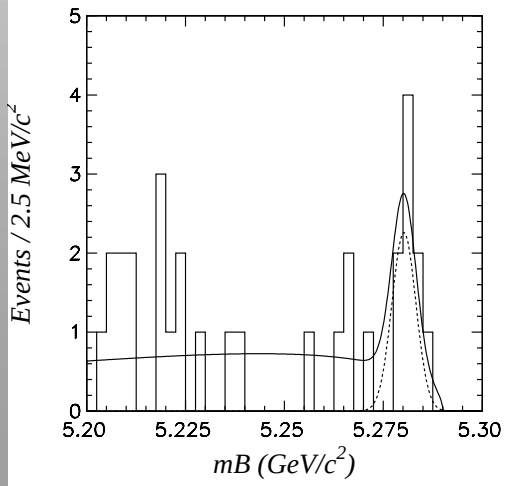
Direct CP modes: B→Kπ, ππ

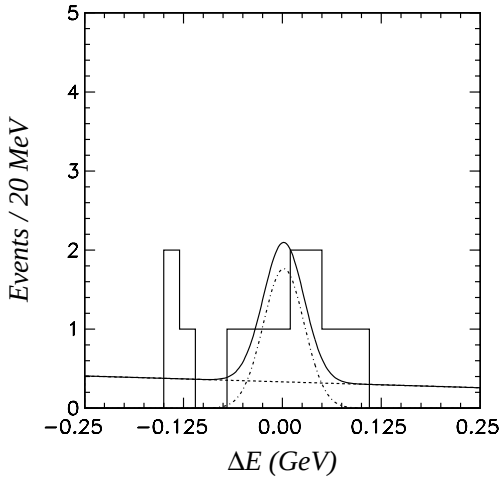
PRELIMINARY





$\pi^+\pi^-$





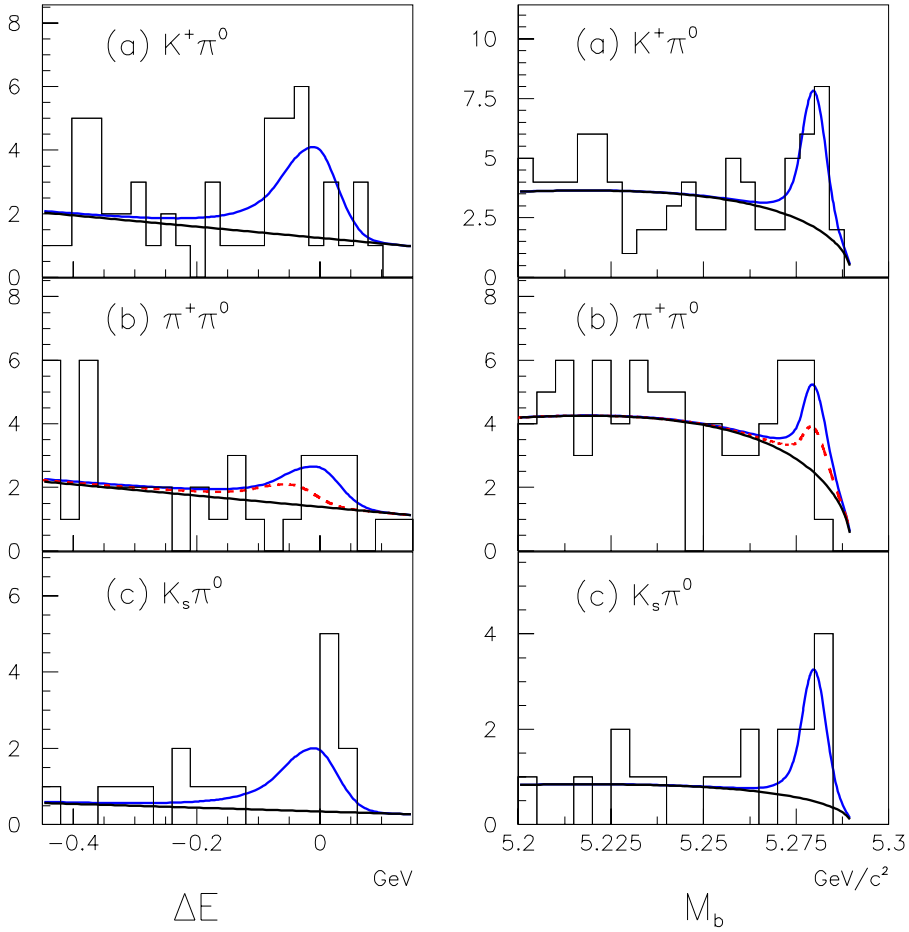
$K^0\pi^+$

Direct CP modes: B→Kπ, ππ

modes with π^0

$\int \mathcal{L} dt$ = 5.3 fb^{-1}

PRELIMINARY



Summary/Prospects

Results on

- sin $2\phi_1$: 6.2 fb^{-1}, 98 tagged events
- first observation of $B \rightarrow \psi K_1(1270)$
- polarization of ψK^*: $CP=+1$ dominates
- Other modes w CP possibilites:

  $D^{(*)}K$, $K\pi$, $\pi\pi$

Next

- More CP modes, flavor tags to be added
- KEKB resumes Oct. 1 w. higher currents