Recent Results From Belle

- Physics Introduction
- KEKB accelerator and Belle detector
- Sin($2\phi_1$) measurement

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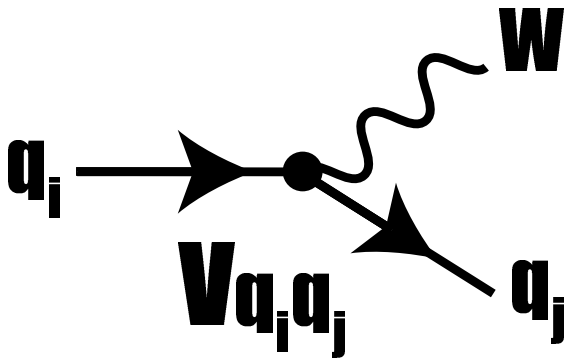
Goal of the Belle Experiment

- Observe CP violation in decays of B meson
- Try to establish the mechanism of the CP violation
  - In particular, we must know whether the measurements (of the CP violation) are consistent with the description given by the CKM matrix of weak interactions in the standard model
  - Otherwise we need to find the new CP violating interaction

CKM Matrix

- The Cabibbo-Kobayashi-Maskawa quark mixing matrix
  - A unitary matrix which relates the mass eigenstates to eigenstates of weak force
  - The strength of the weak interaction is proportional to $V_{q_i q_j}$
  - Wolfenstein parameterization is the most popular approximation, writing in terms of the powers of λ;sine of Cabibbo angle

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



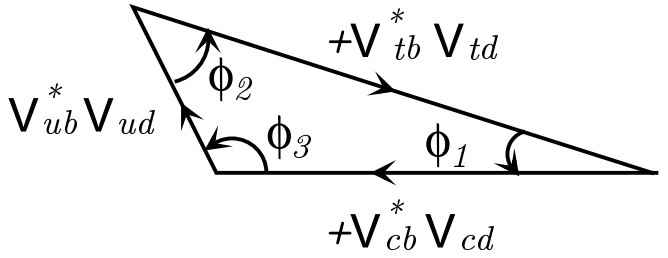
$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity Triangles

- Unitarity of the CKM matrix applied to the first and third columns yields

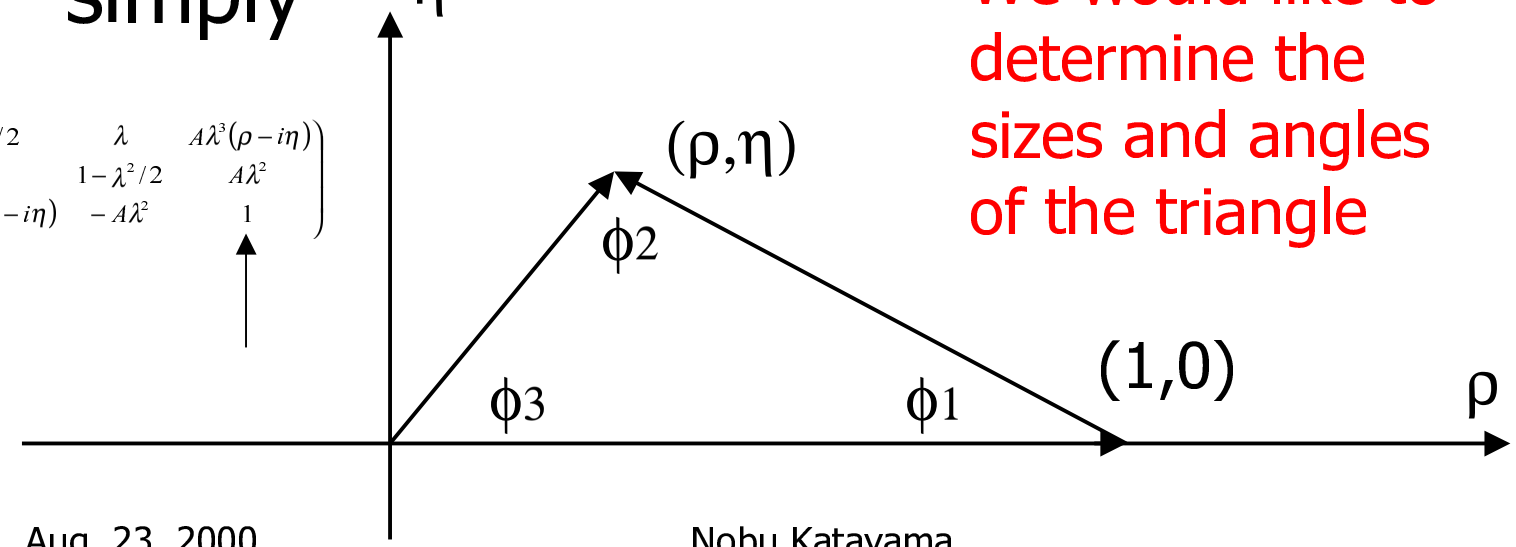
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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



- In the Wolfenstein parameterization, it is simply

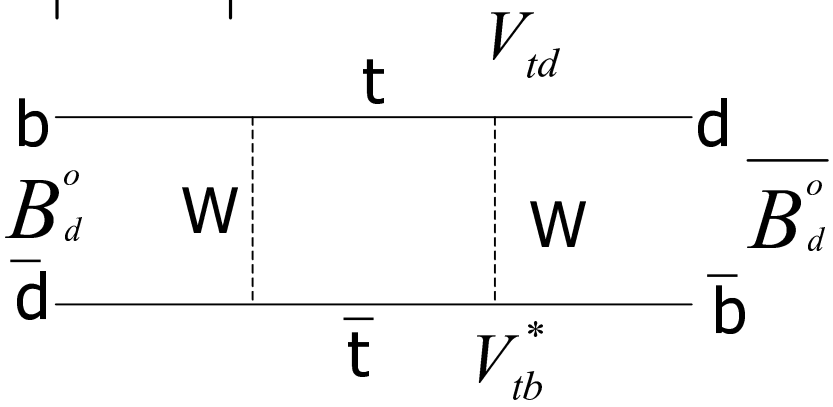
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



We would like to determine the sizes and angles of the triangle

B Mixing

- $B^o_d - \overline{B^o_d}$ mixing measures $\left|V_{td}V^*_{tb}\right|$
- $B^o_d - \overline{B^o_d}$ mixing was first observed by ARGUS and confirmed by CLEO

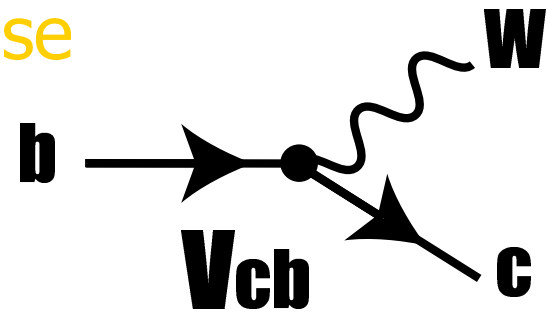


  - The large mixing was a surprise
  - LEP experiments/CDF/SLD have measured the mass difference of $B_{d,+}$ and $B_{d,-}$, Δm_d precisely

$$\Delta m_d = 0.473 \pm 0.016\ ps^{-1} \quad \text{(PDG2000)} \qquad \left|V_{td}V^*_{tb}\right| = 0.0083 \pm 0.0016$$

Lifetime of B meson

- Lifetimes of the B mesons are also measured very precisely at LEP/CDF/SLD
  - The long lifetime was a surprise
- B lifetime determines $|V_{cb}|$



- Keep in mind that
  - Δm_d and the lifetimes are fundamental parameters and are necessary ingredients for the measurement of the CP violation
  - Now at the asymmetric B factories, because B mesons are moving, they can be measured

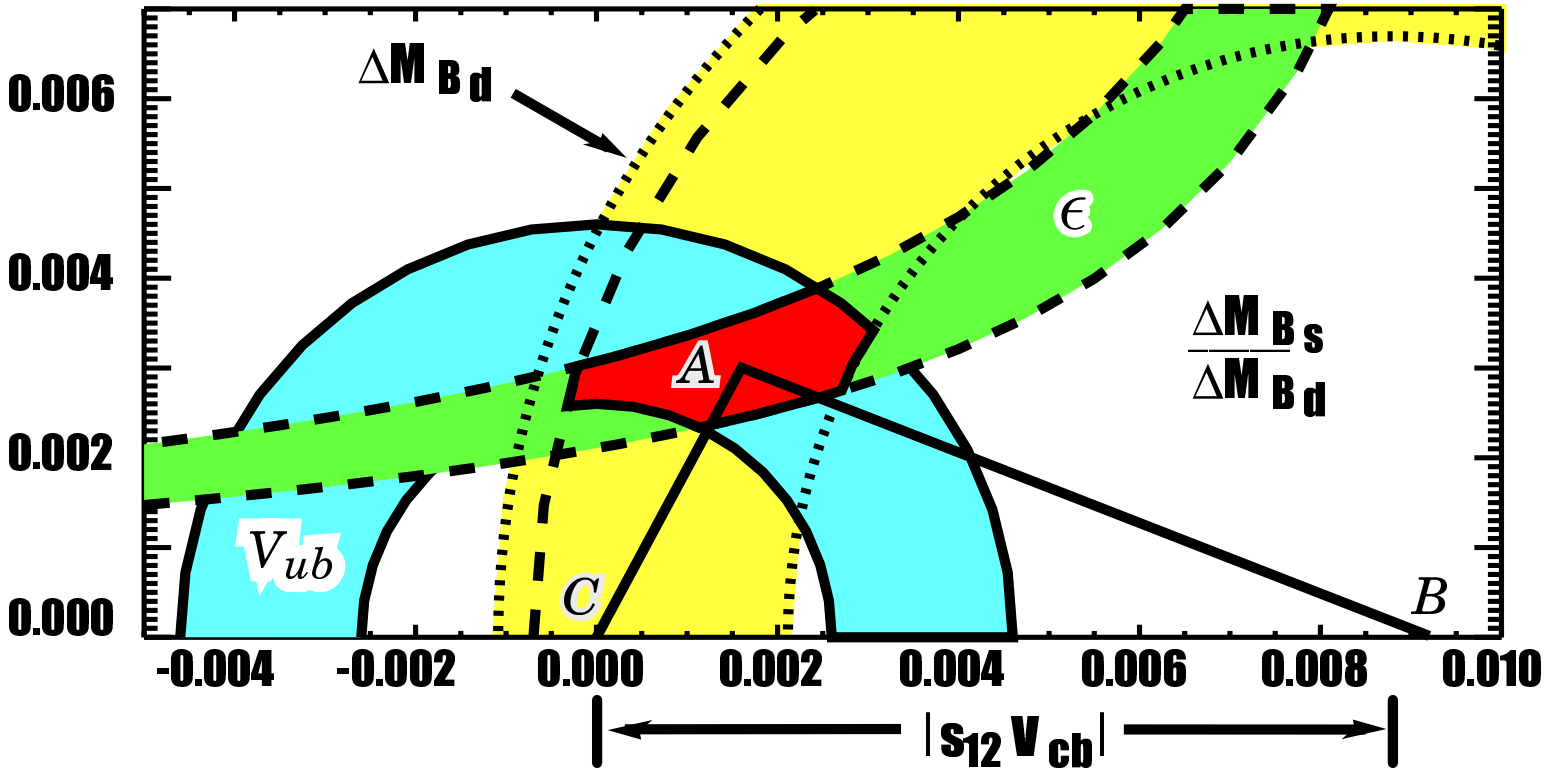
CP Violation in the Standard Model

- In the standard model, CP-violating processes/amplitudes involve the phase in the CKM matrix
  - A 3x3 unitary matrix has one non-trivial phase
- For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry and sin(2ϕ)
  - Asymmetry in the golden mode, $B_d^o \left(\overline{B_d^o} \right) \to J/\psi K_S$ determines sin(2ϕ_1)

$\phi_1 \equiv \beta$

The Unitarity Triangle Constrained

- Other measurements (ε, b→u, etc.) constrain the triangle in other ways
- The CKM matrix given in PDG2000



How to Measure sin($2\phi_1$) at Υ(4S)

1. Reconstruct the B meson decay into the CP eigenstates
2. Tag the flavor of the other B decay
3. Measure the signed time difference Δt
   - The asymmetry A(Δt) will distribute as

$$A(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} \propto \eta_{CP} \sin 2\phi_1 \sin \Delta m_d \Delta t$$

Asymmetric e^+e^- collider

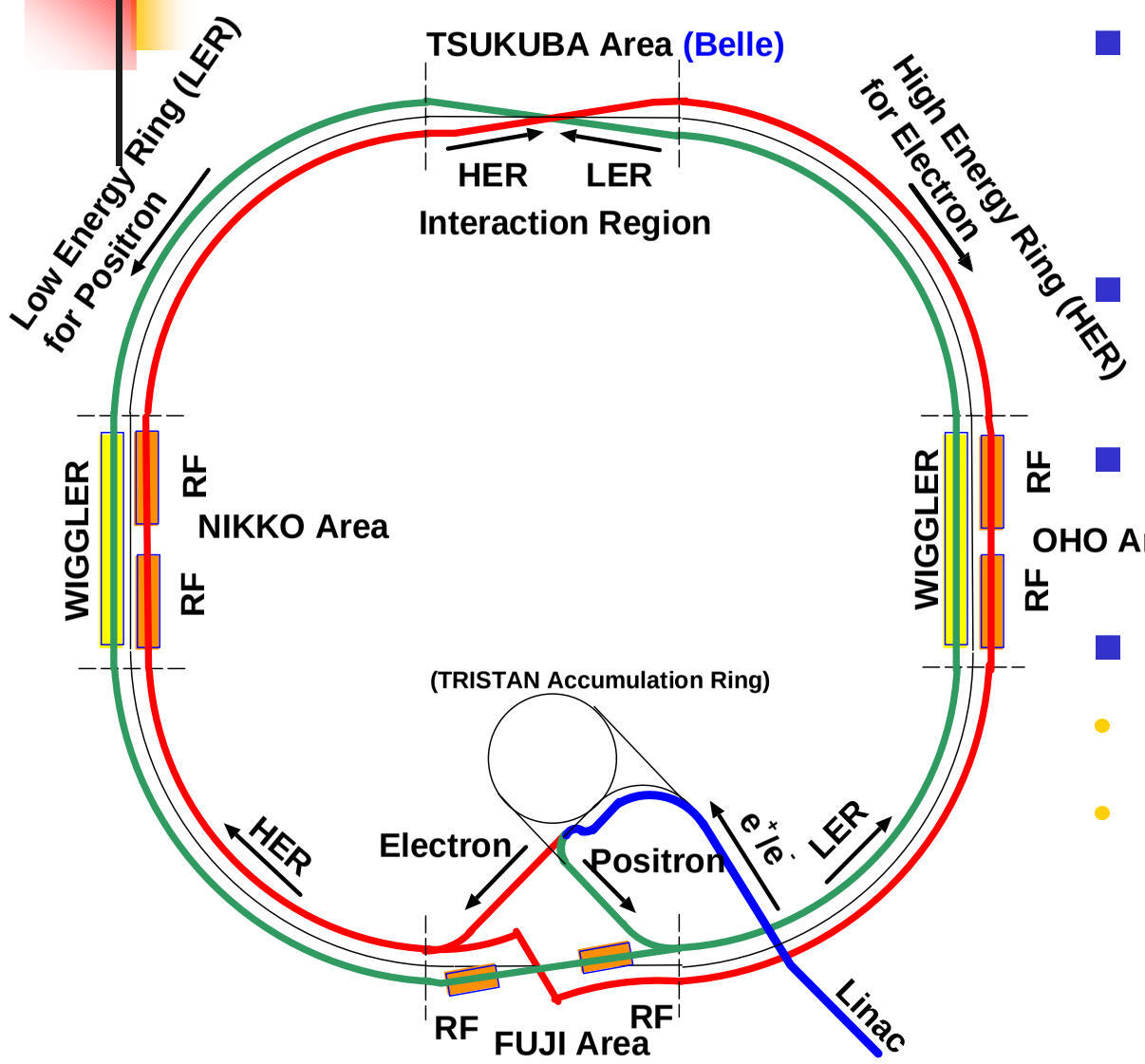
⇓⇓⇓

B mesons are moving

KEK

- National High Energy Physics Laboratory in Japan
- KEKB and Belle
- ATLAS
- K2K
- (JHF)
- …

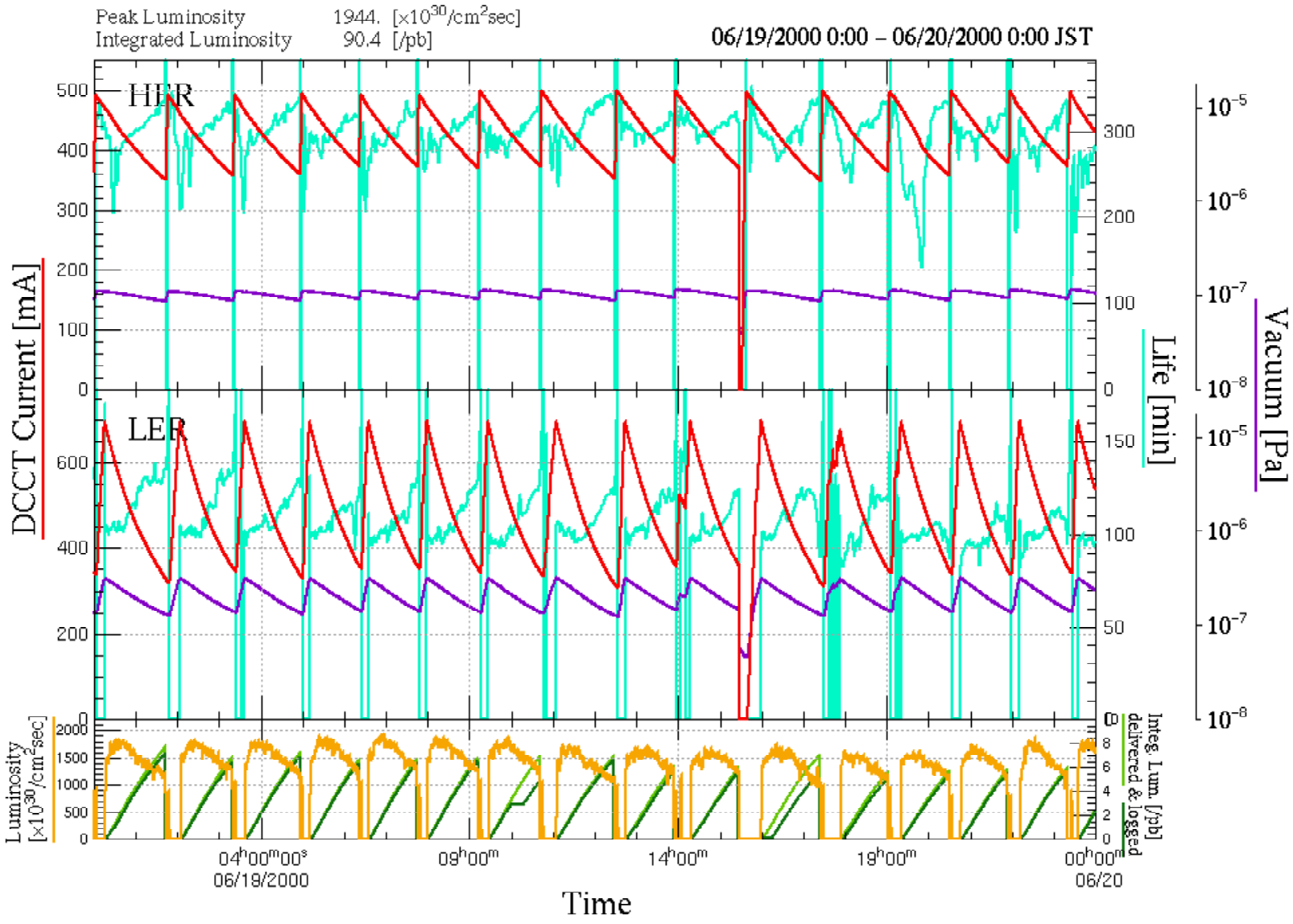
The KEKB Collider



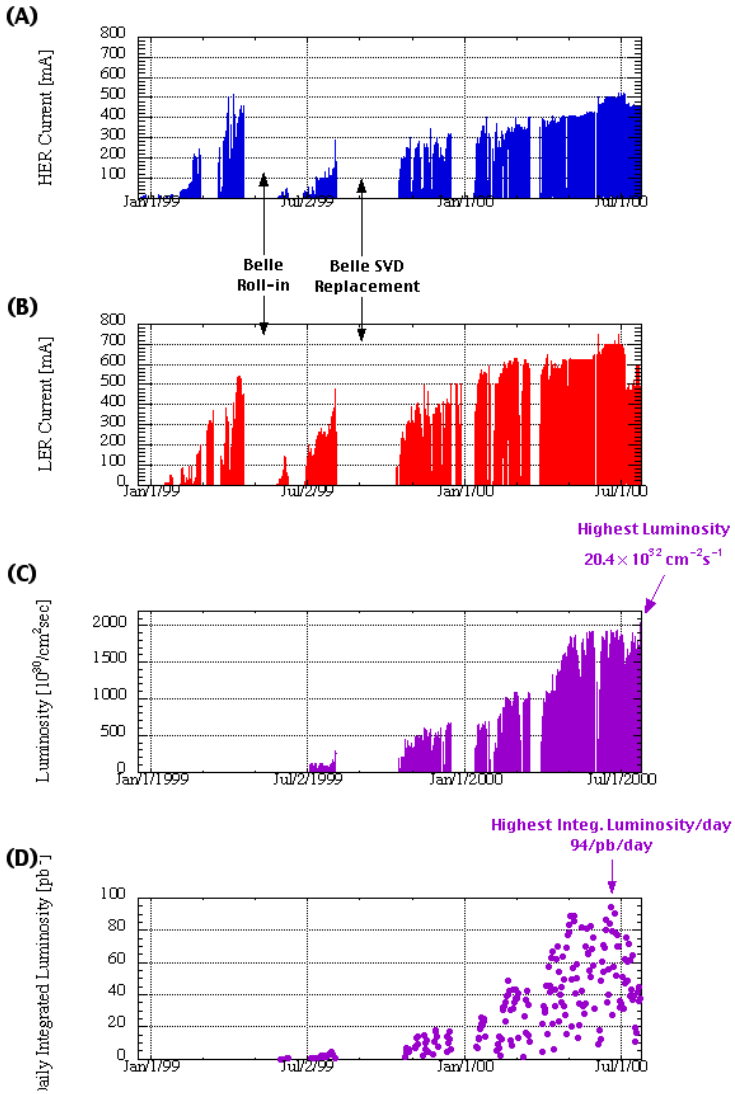
- Asymmetric e^+e^- collider (3.5GeV vs 8.0GeV)
- Reuse TRISTAN tunnel
- $L_{goal}=10^{34}\ cm^{-2}s^{-1}$
- History
  - **First collision :June 1999**
  - **Physics run so far:**
    Oct. 1999 – July 2000

$$\int Ldt = 6.8\ fb^{-1}$$

One Day Performance (June 19)



KEKB Performance



Parameters of KEKB (7/23/2000) Achieved/Design(model)

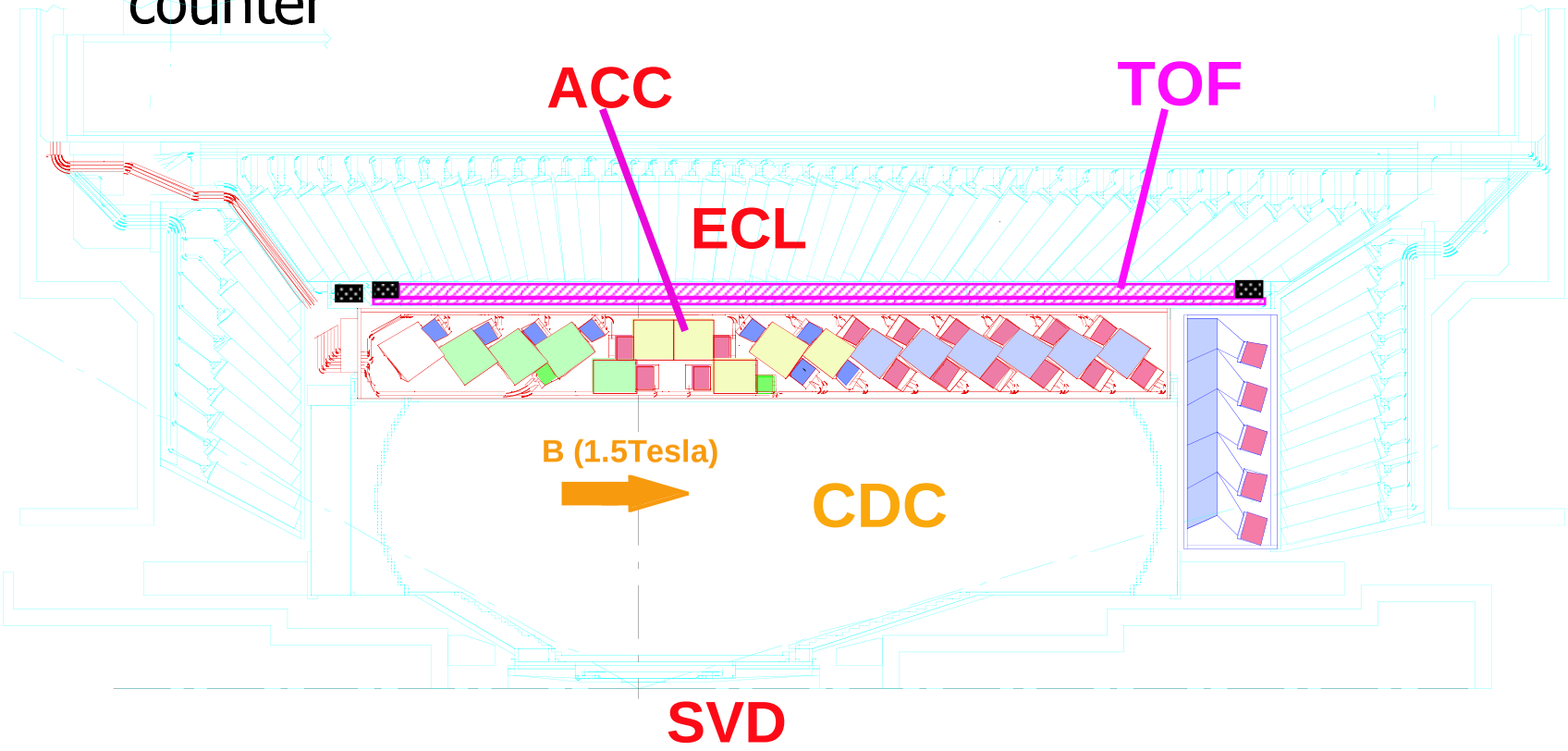
	LER	HER	
Horizontal Emittance	18	30	nm
Beam current	465 (2600)	420 (1100)	mA
Number of bunches	1146 (2700)		
Bunch current	0.41 (0.96)	0.37 (0.41)	mA
Bunch spacing	2.4 (1.2)		m
Bunch trains	8 (159 bunches each)		
Horizontal size at IP $\Sigma_x/\sqrt{2}$	112 (112)	145 (145)	μm
Vertical size at IP σ_y^*	1.7 (1.12)	1.7 (1.45)	μm
Emittance ratio $\varepsilon_x/\varepsilon_y$	2.3 (1)	1.4 (1)	%
β_x^*/β_y^*	70 / 0.7	70 / 0.7	cm
beam-beam parameters ξ_x/ξ_y	0.036 / 0.037 (0.05 / 0.05)	0.029 / 0.023 (0.05 / 0.05)	
Beam lifetime	130 @ 465 mA	180 @ 420 mA	min.
Luminosity (Belle CSI)	20.4×10^{32}		$cm^{-2}s^{-1}$
Luminosity record per day / per week	94 / 504		pb^{-1}

The Belle Collaboration

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.
ICRR, University of Tokyo
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 Kaohsiung Normal University
National Lien-Ho Institute of Technology
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

The Belle Detector

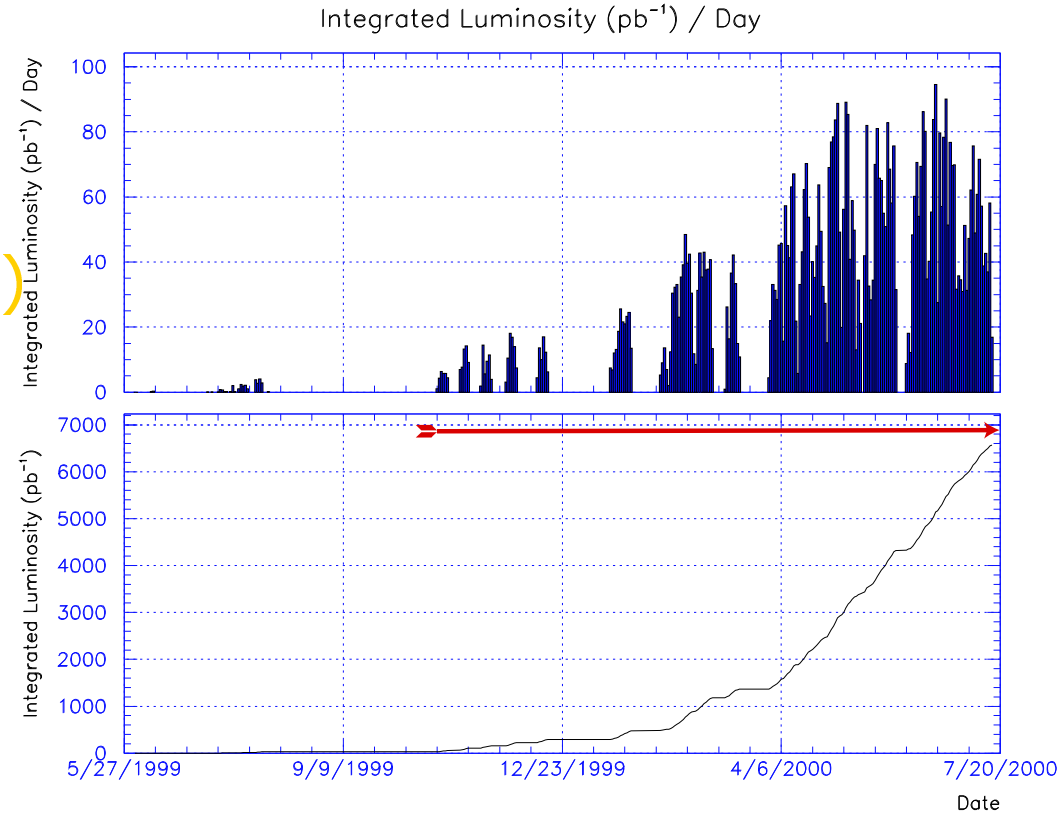
- SVD:3lyr silicon detector
- CDC:50 lyr drift chamber
- ACC:Aerogel Cherenkov counter
- TOF:4cm Scint. Counter
- ECL:16 rad. len. CsI
- KLM:14lyr RPC



Dataset

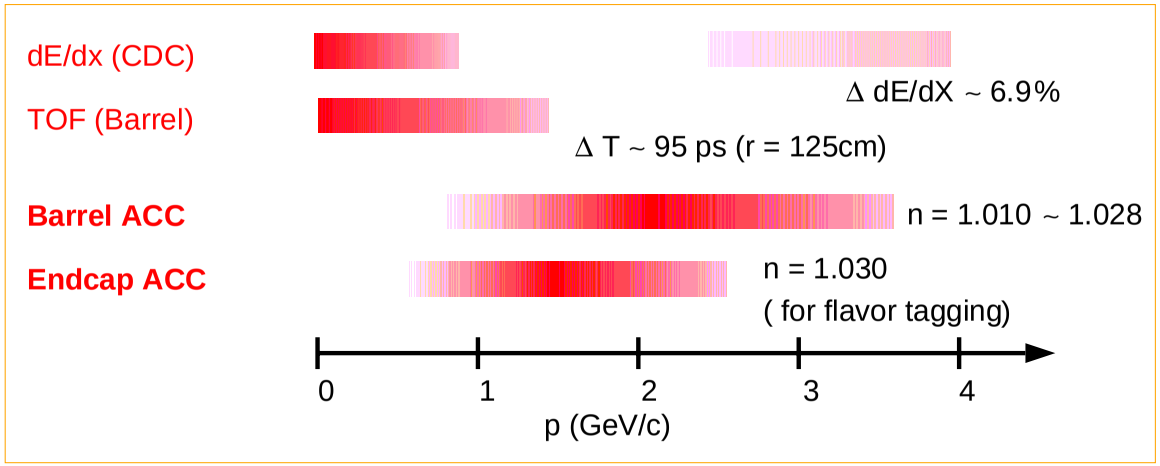
- In the following analyses we use 6.2 fb^{-1} of data taken at the Y(4S) peak during Oct. '99 --- July 2000 run.

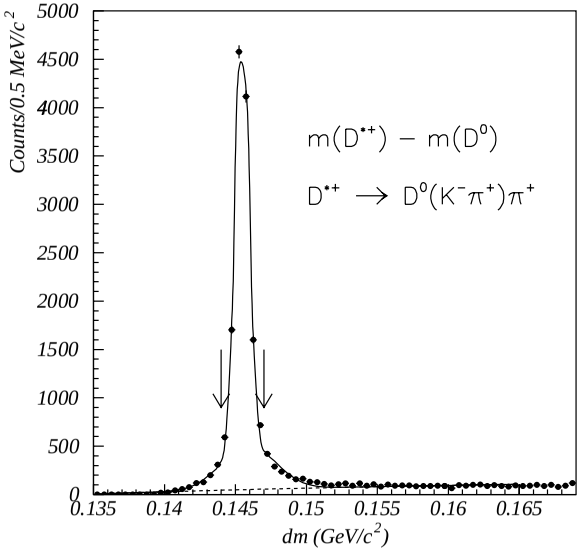
- Some figures and/or numbers are made with less data (5.1fb^{-1} on resonance taken by June)
- 0.6 fb^{-1} continuum data are also used in the background study
- All numbers are, of course, preliminary

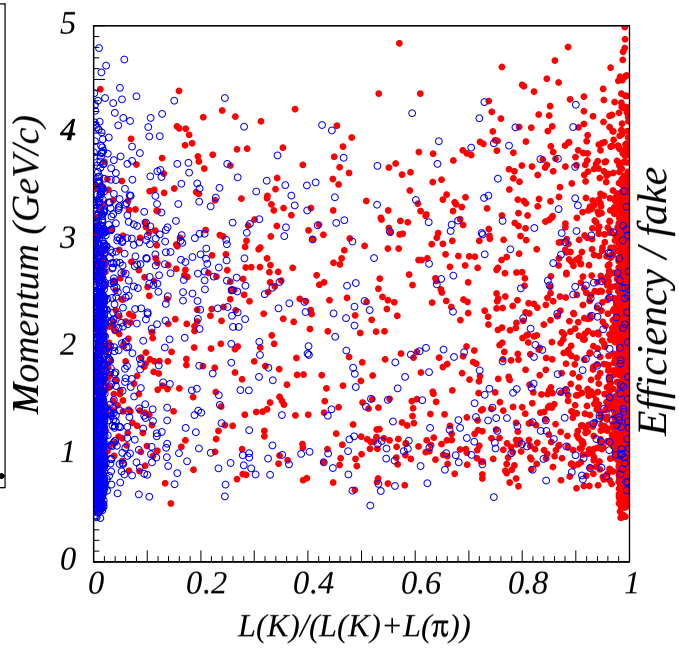


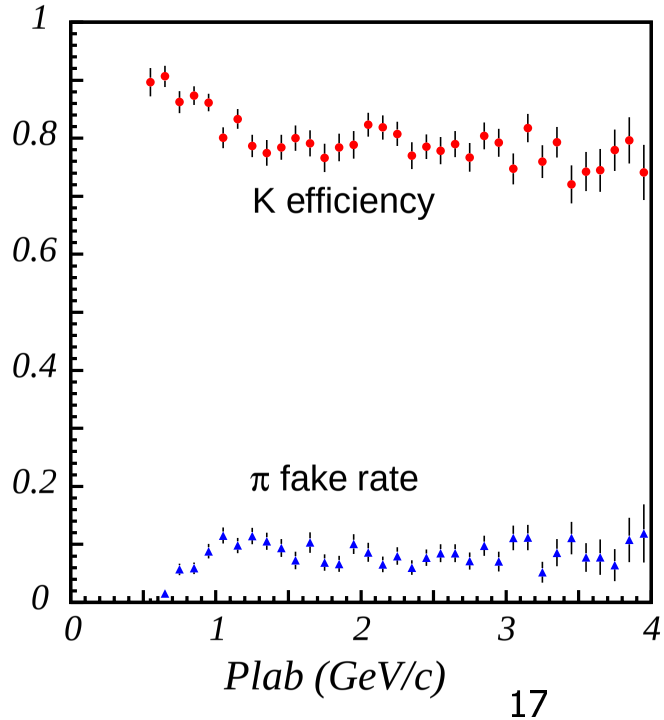
Kaon Identification

- Efficiency's been measured using D^o decay to $K\pi$ with D* tag



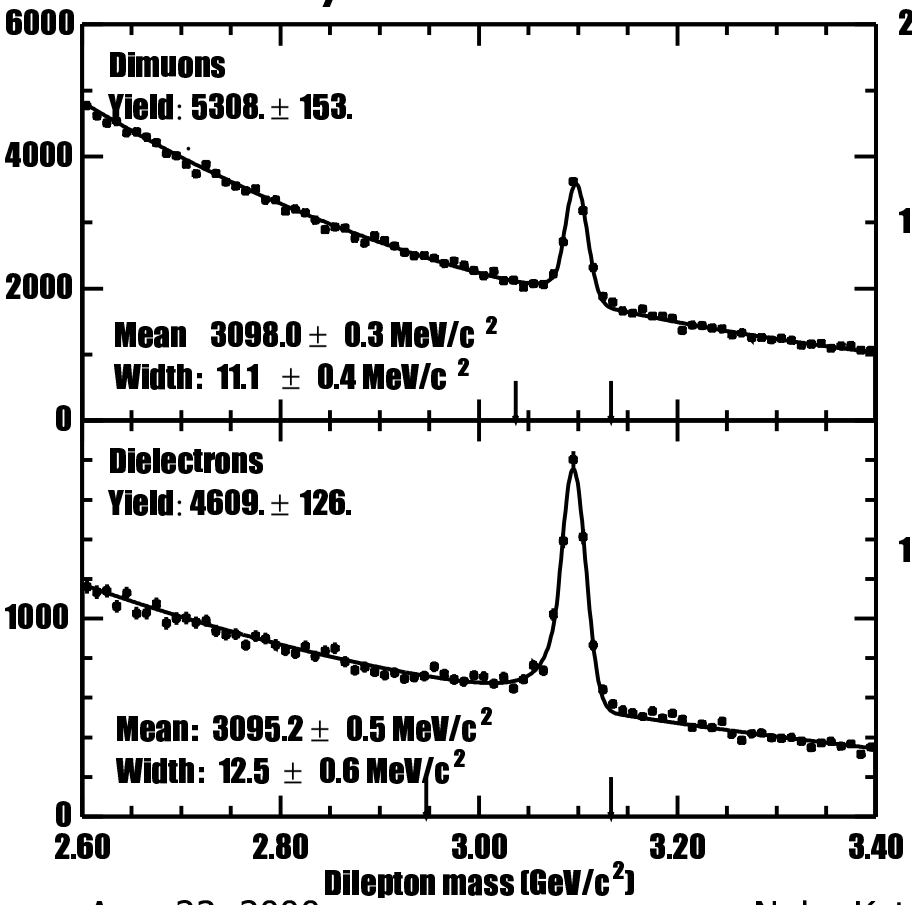


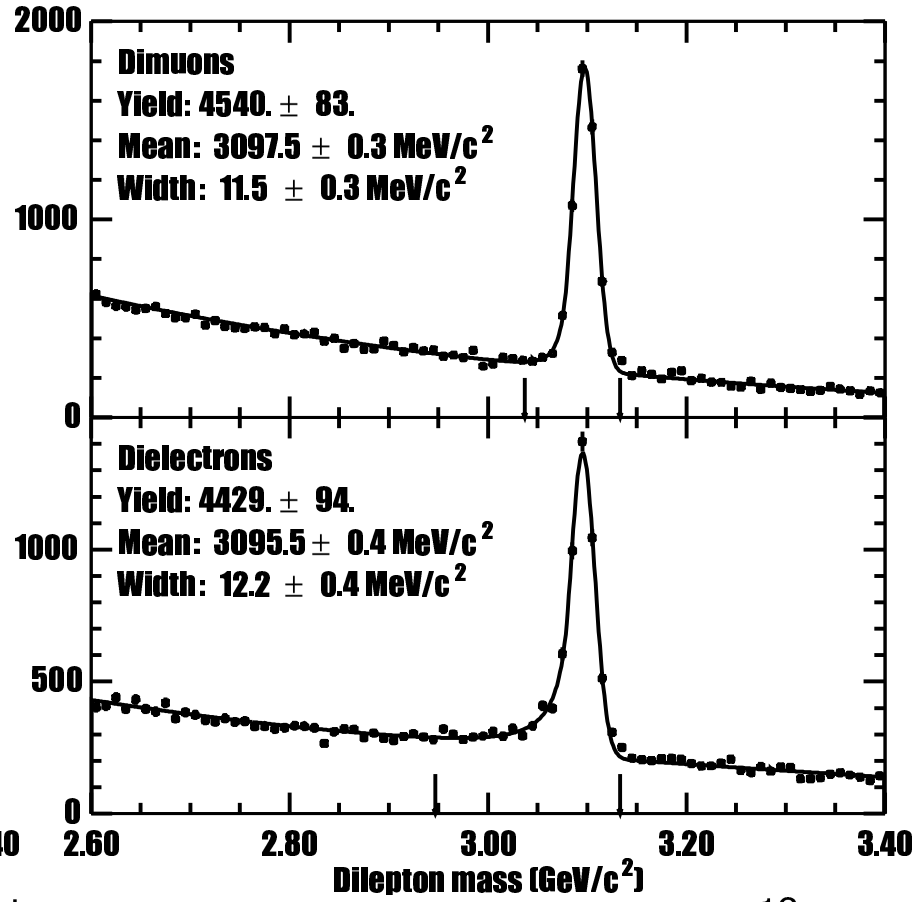




Lepton Identification $J/\Psi \to \ell^+ \ell^-$

- One lepton is tightly identified, the other loosely
- Both leptons are tightly identified





How to Measure $\sin(2\phi_1)$ at Belle

- Reconstruct the B meson decay into the CP eigenstates
- Tag the flavor of the other B decay
- Measure the signed time difference Δt
  - The asymmetry $A(\Delta t)$ will distribute as

Asymmetric e^+e^- collider
⇓⇓⇓
B mesons are moving

$$A(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} \propto \eta_{CP} \sin 2\phi_1 \sin \Delta m_d \Delta t$$

- Experimental concerns
  - Resolution function
  - Wrong tagging fraction
  - Backgrounds

Must understand these very well

How to Measure Lifetimes & Mixing

- Reconstruct (at least partially) two B mesons and identify flavor of the two B mesons (mixing case) /determine whether they are charged or neutral
- Measure the (signed) time difference Δt
  - Mixing:

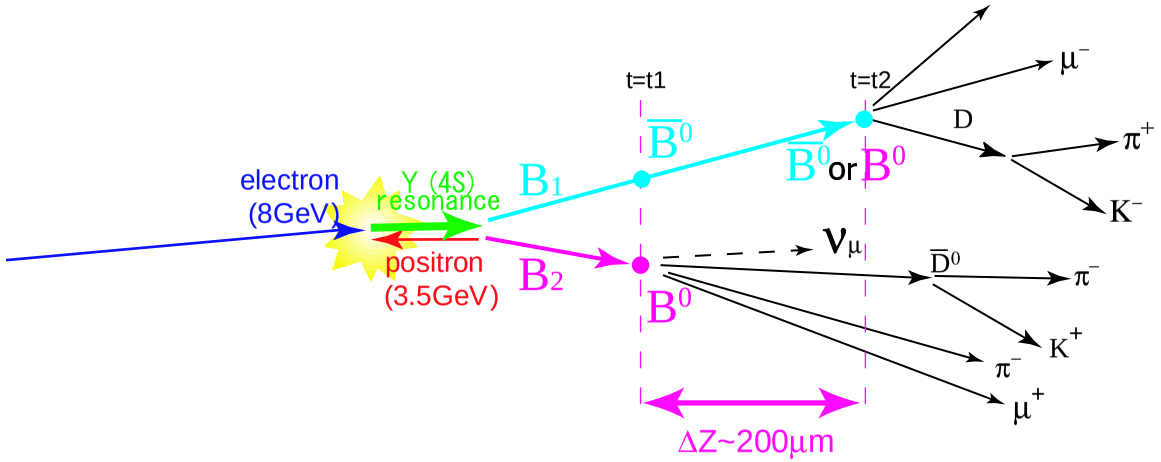
$$P_{\text{same/opposite}}(\Delta t) \propto e^{-|\Delta t|/\tau}\left[1 \pm (1-2w)\cos\Delta m_d \Delta t\right]$$

  - Lifetimes:

$$P_{\text{charged/neutral}}(\Delta t) \propto e^{-|\Delta t|/\tau_{\text{charged/neutral}}}$$

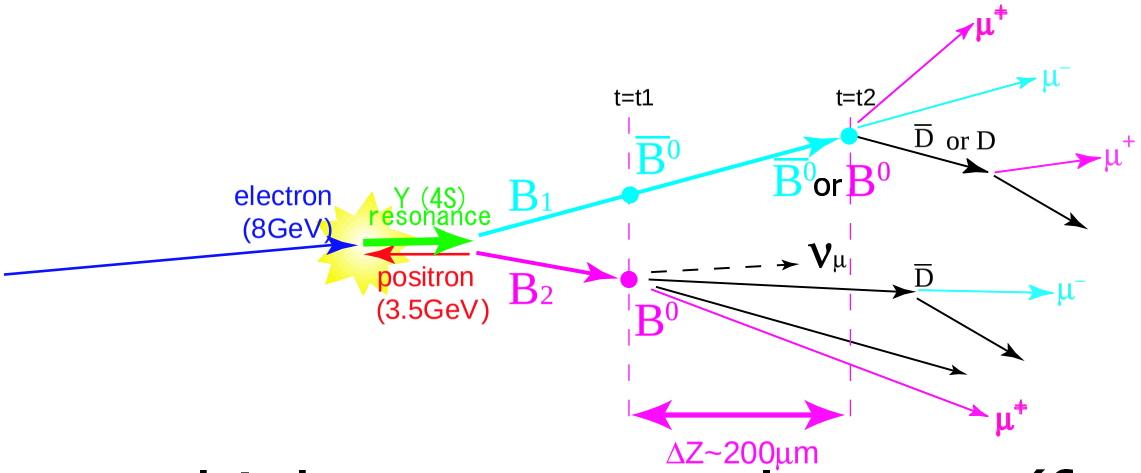
- These are the benchmark measurements to demonstrate that ~~CP~~ can be measured

Measuring B Lifetime and Mixing



- Electron with energy of 8GeV and positron, 3.5GeV, collide into Υ(4S) which immediately decays into B and $\bar{B}$ mesons.
- The B's fly at $\beta\gamma=0.425$ and decay with $\tau\approx1.5$ps
- To measure the lifetime and/or mixing parameter, we need to "reconstruct" both B mesons as we can only measure the decay (time) difference

Mixing with Dileptons

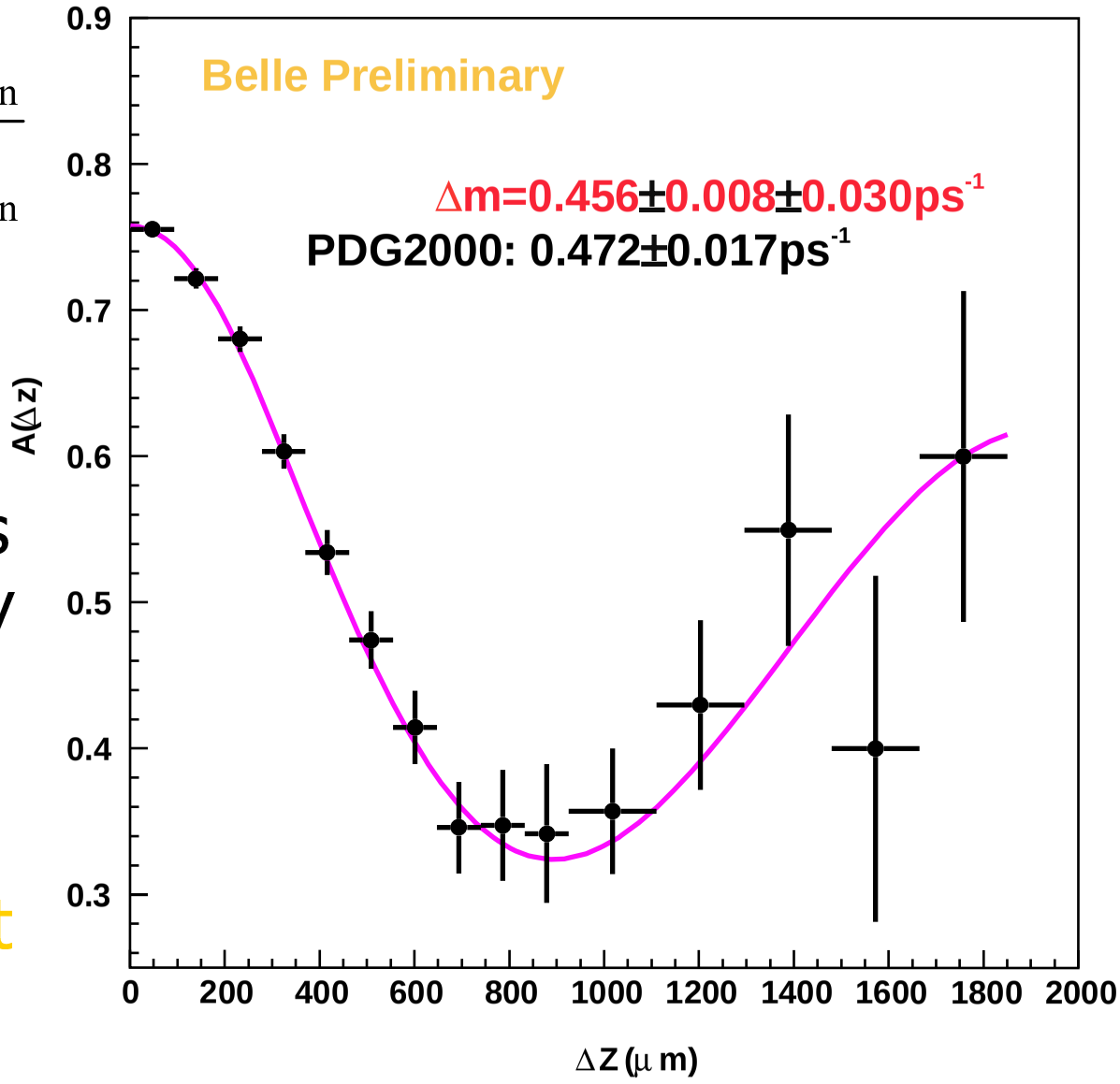


- Identify two high momentum leptons (from b→clν)
  - Same sign dileptons
    - Primary dileptons from mixed events
    - Primary + secondary from unmixed and B^+B^- events
    - Backgrounds
  - Opposite sign dileptons
    - Primary dileptons from unmixed and B^+B^- events
    - Primary + secondary from mixed events
    - Backgrounds

Dilepton Asymmetry

$$\frac{N_{\text{opp. sign}} - N_{\text{same sign}}}{N_{\text{opp. sign}} + N_{\text{same sign}}}$$

- Measure the decay distance of opposite sign and same sign dileptons and plot asymmetry as a function of Δz
- Note: The curve shown is the result of the fit, not the fit to this histogram



Mixing Measurement Using $D^{(*)}l\nu$

- In the dilepton events, backgrounds from the charged B decays cannot be avoided
- Use (semi) exclusive, flavor specific decays to "tag" the neutral B mesons
- Identify the flavor of the other B meson
  - The same "flavor tagging methods" in the CP measurement are used and we can determine w(wrong sign fraction) and Δm_d from the fit to the following distributions

$$P_{opposite-flavor}(\Delta t) \propto e^{-|\Delta t|/\tau}\left[1+(1+2w)\cos(\Delta m_d \Delta t)\right]$$

$$P_{same-flavor}(\Delta t) \propto e^{-|\Delta t|/\tau}\left[1-(1-2w)\cos(\Delta m_d \Delta t)\right]$$

$D^{(*)}l\nu$ Asymmetry and Flavor Tagging

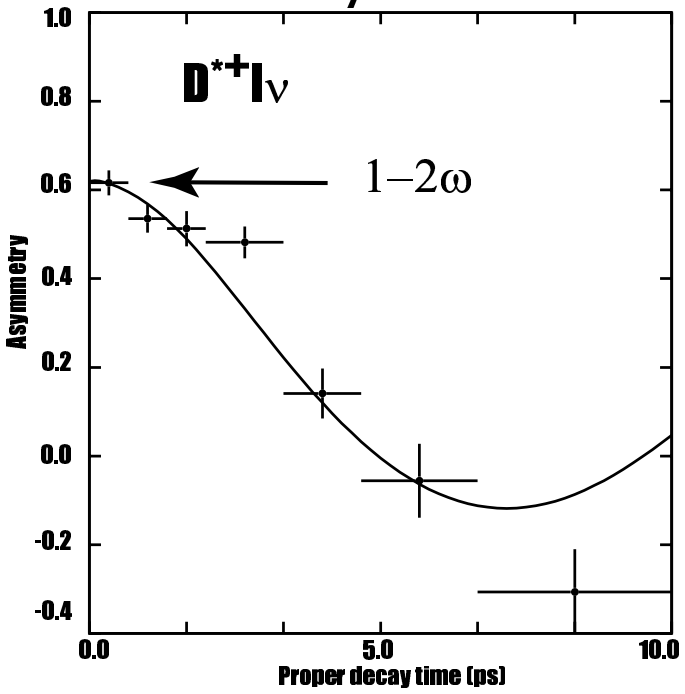
- From the measured asymmetry we obtain

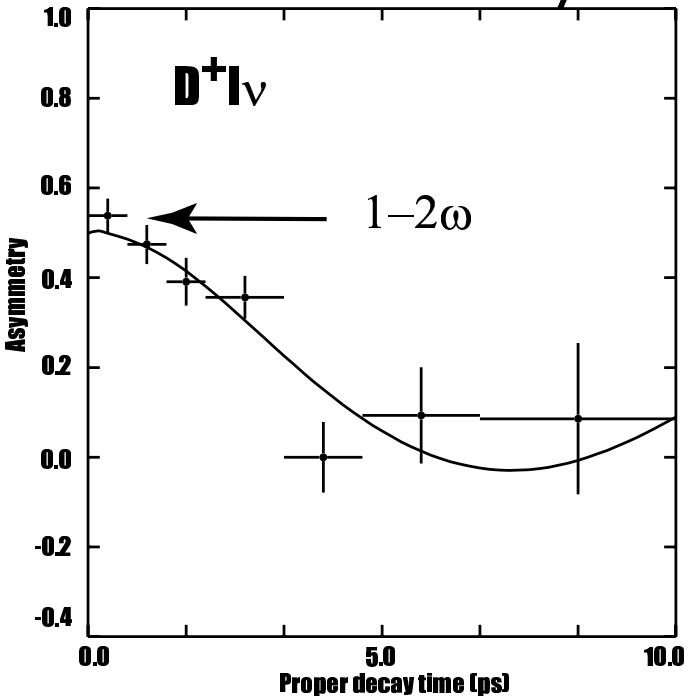
$$\Delta m_d = 0.488 \pm 0.026(stat.)\, ps^{-1}$$
$$w_{lepton} = 0.071 \pm 0.019(stat.)$$
$$w_{Kaon} = 0.199 \pm 0.021(stat.)$$

Belle Preliminary

$$A(\Delta t) = \frac{P_{opposite-flavor}(\Delta t) - P_{same-flavor}(\Delta t)}{P_{opposite-flavor}(\Delta t) + P_{same-flavor}(\Delta t)} \approx (1-2w)\cos(\Delta m_d \Delta t)$$

- Systematic errors are under study

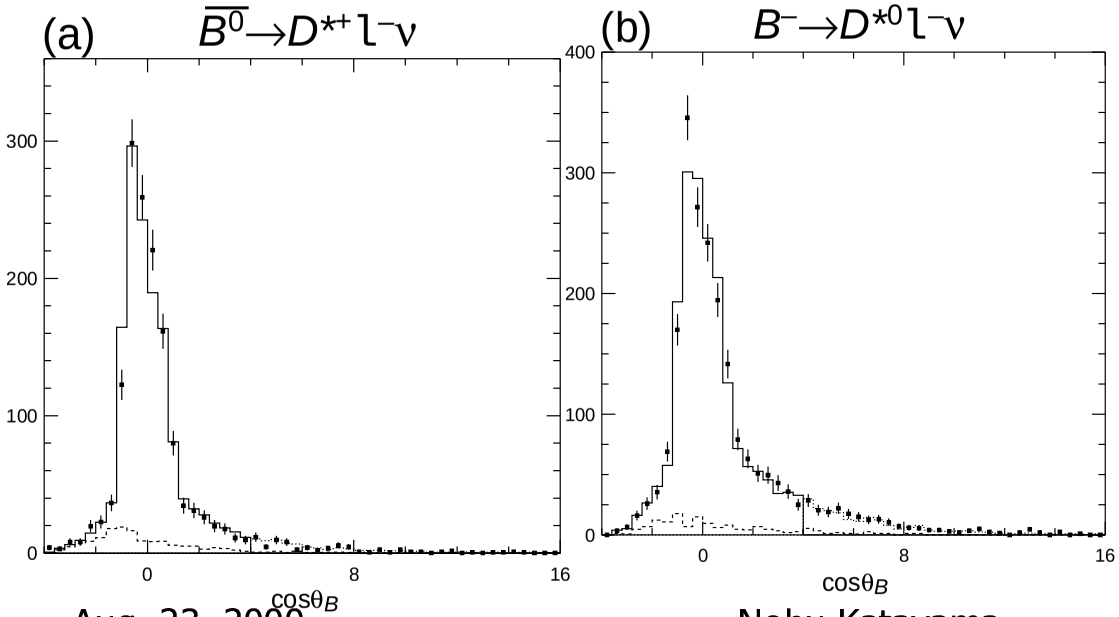


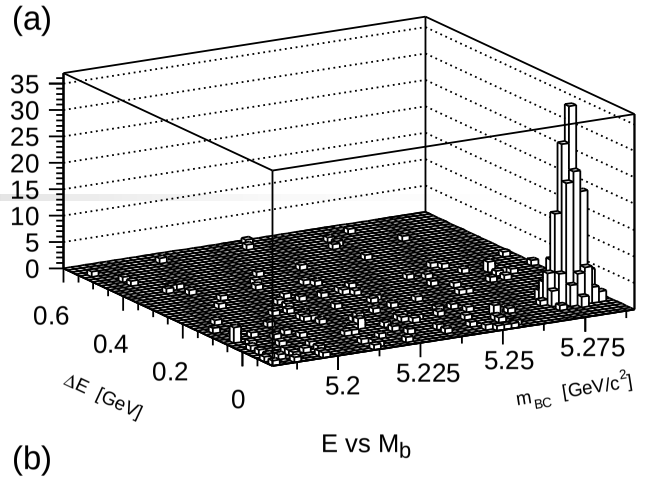


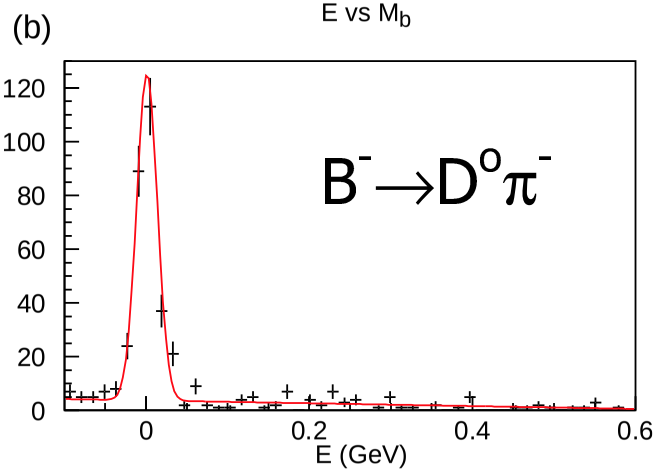
By "≈" we mean that the resolution function, R(Δt) need to be convoluted. Will be discussed later. Our resolution in Δt is about 1.2ps.

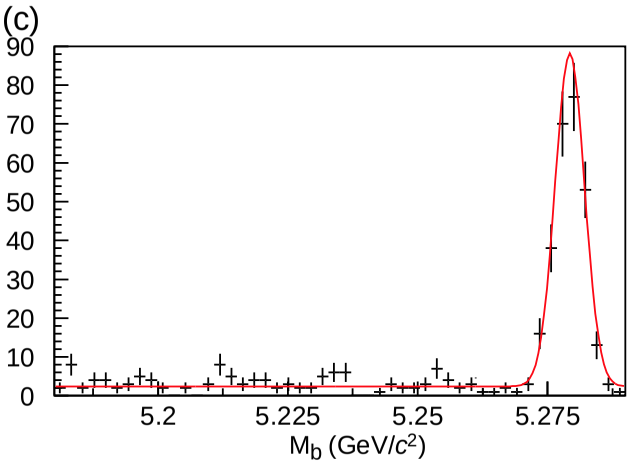
B Meson Lifetimes

- Again, use the (semi) exclusive decays to "tag" the charged/neutral B mesons to measure the lifetimes of charged and neutral B mesons separately









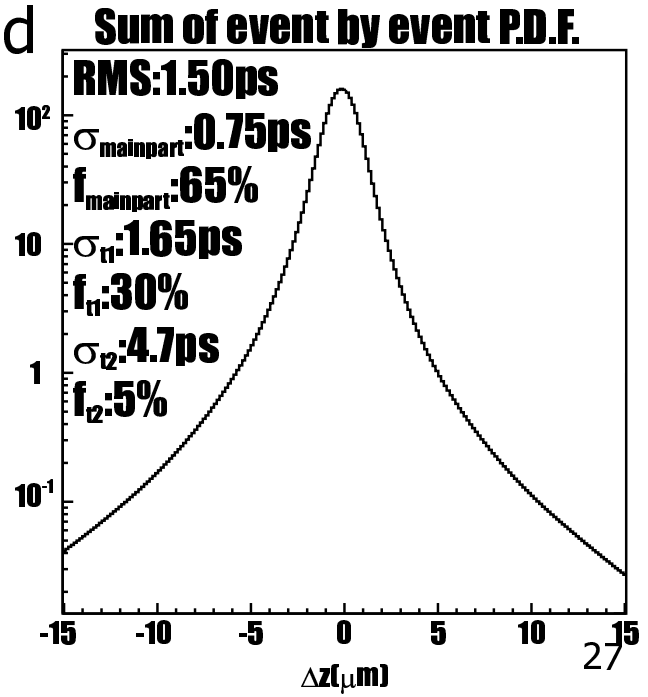
B Lifetime Fit

- Event by event probability density function

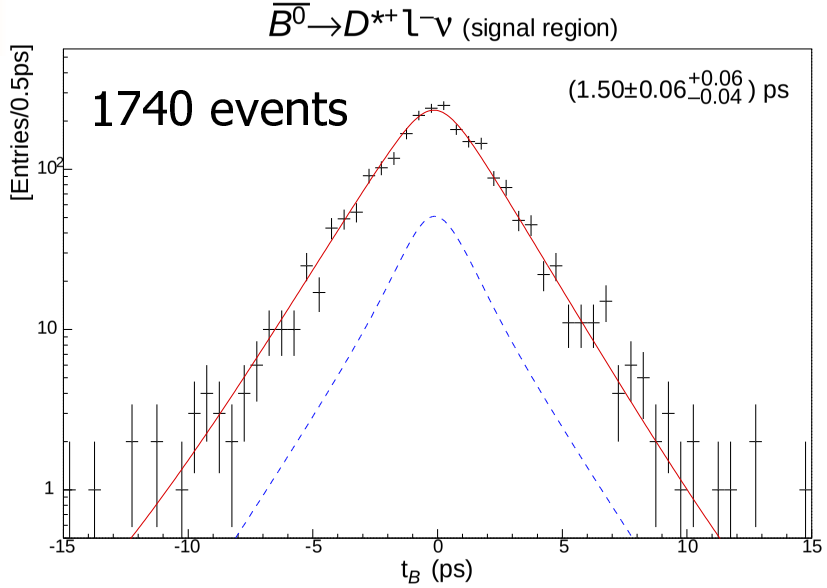
$$P(\Delta t) = f_{SIG}\int_{-\infty}^{\infty} d(\Delta t')\frac{e^{-|\Delta t|/\tau_{SIG}}}{2\tau_{SIG}} R_{SIG}(\Delta t - \Delta t') + (1-f_{SIG})\int_{-\infty}^{\infty} d(\Delta t')[f_{\lambda_{BG}}\frac{\lambda_{BG}}{2}e^{-|\Delta t'|\lambda_{BG}} + (1-f_{\lambda_{BG}})\delta(\Delta t')]R_{BG}(\Delta t - \Delta t')$$

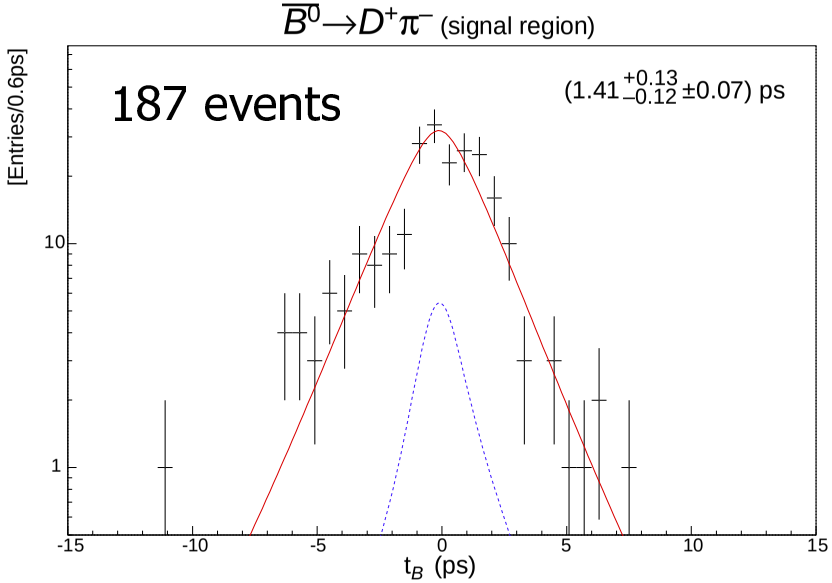
  - τ_B:B lifetime
  - f_{sig}:signal probability calculated event by event
  - λ_{BG}:exponential tail of the background component
  - $f_{\lambda BG}$:Fraction of the background

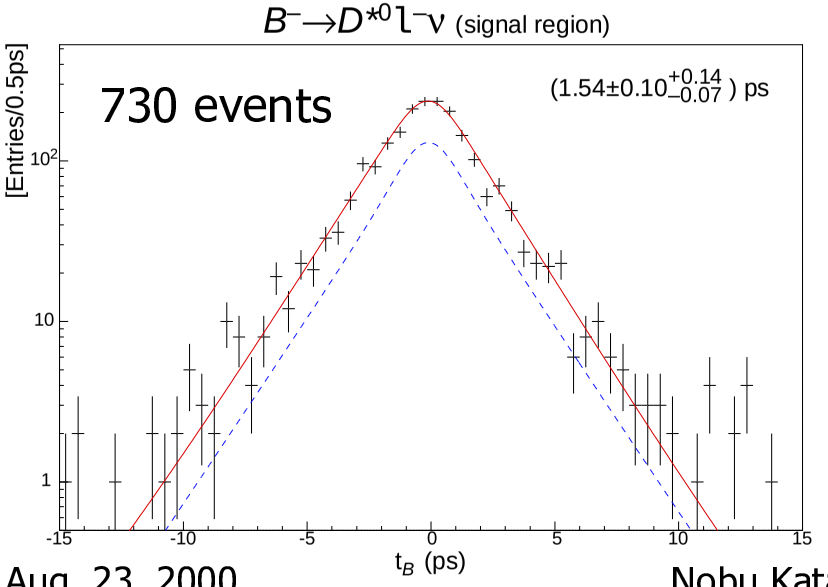
- R_{sig}:response function
  - Double Gaussian (main and tail scaling factors) using error calculated event by event
  - Main scaling factor is determined using continuum charm decays
  - Tail scaling factor is determined in the fit

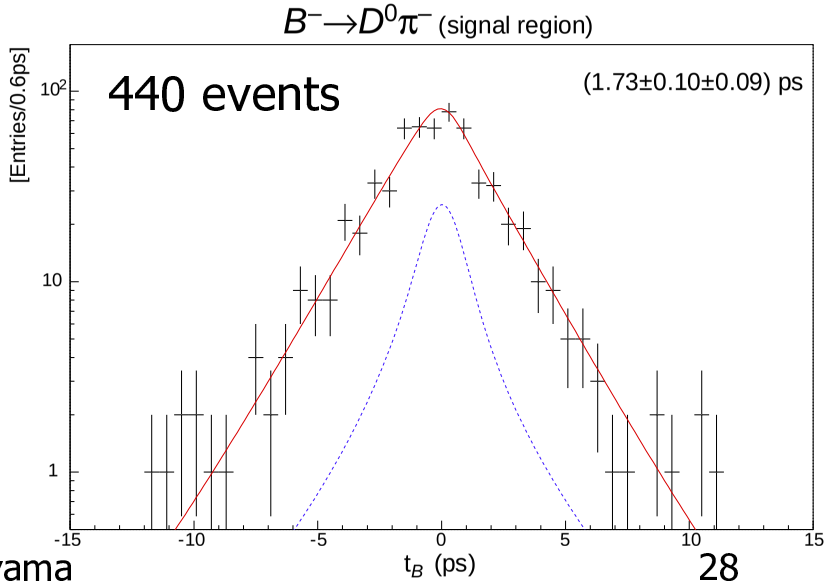


B Lifetime Fits (B→D)





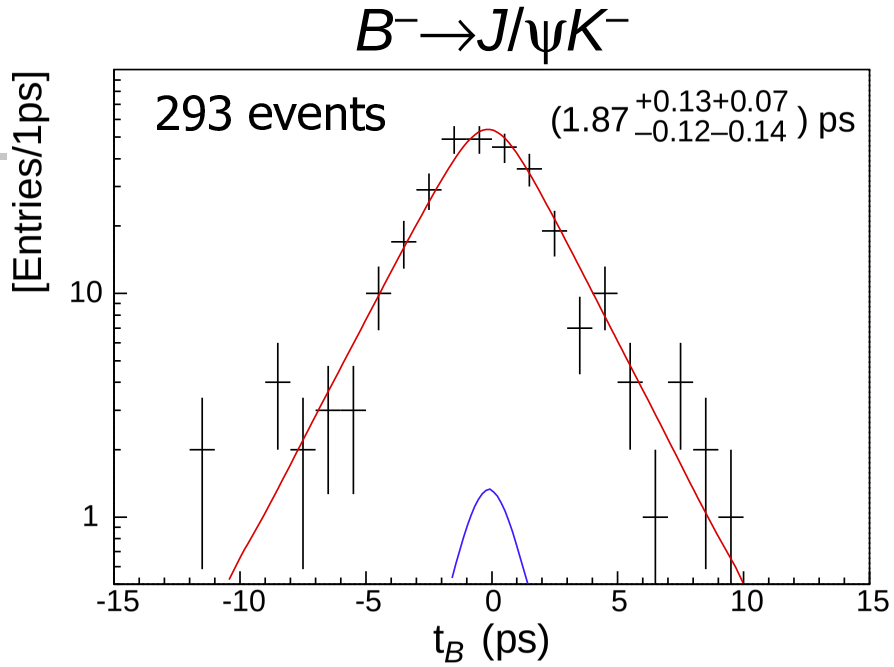


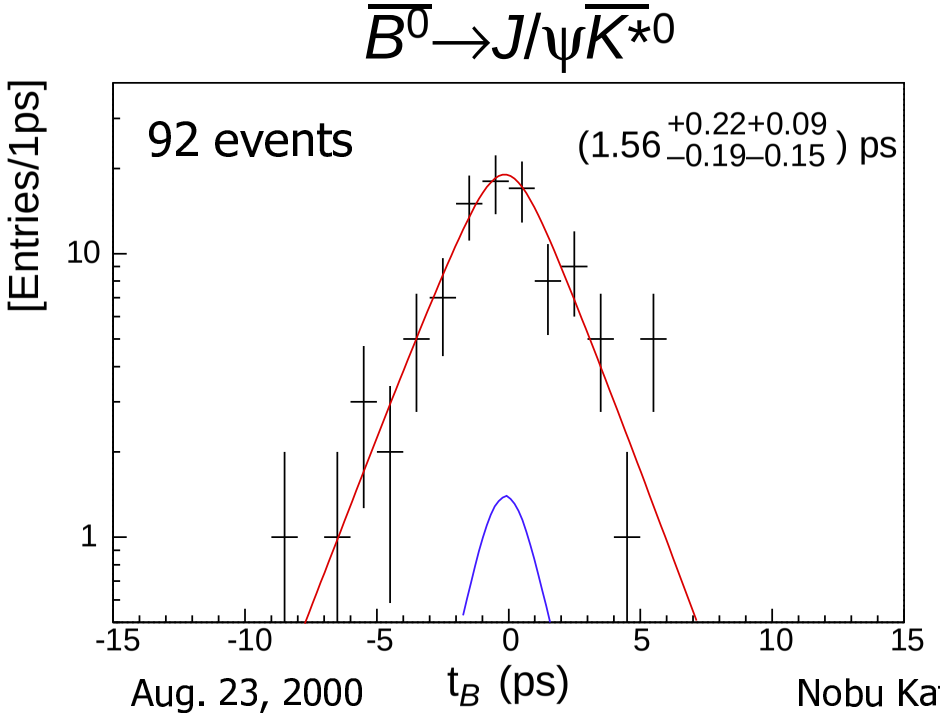


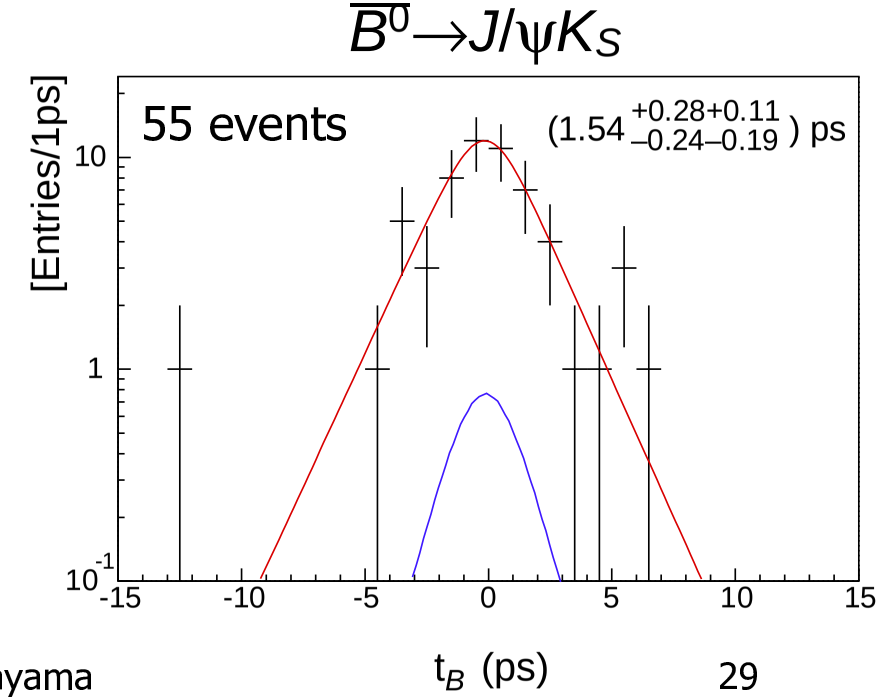
B Lifetime Fits

B→J/ΨK

- This is to show we can measure Δt for J/ψK events (important for CP measurement)







B Lifetimes and Mixing : Summary

- B^0 lifetime measurement

$$\tau = 1.50 \pm 0.05 \pm 0.07\, ps \quad (PDG2000 : 1.548 \pm 0.032\, ps)$$

- B^+ lifetime measurement

$$\tau = 1.70 \pm 0.06^{+0.11}_{-0.10}\, ps \quad (PDG2000 : 1.653 \pm 0.028\, ps)$$

- Mixing measurement (dilepton)

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

$$(PDG2000 : 0.472 \pm 0.017\, ps^{-1})$$

- Mixing measurement (D*lν)

$$\Delta m_d = 0.488 \pm 0.026(stat.)\, ps^{-1}$$

- All results are preliminary but

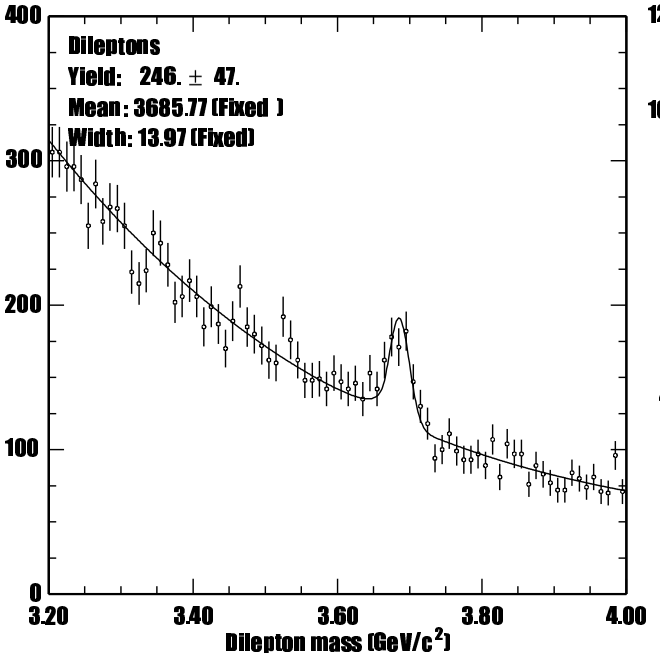
  Now we are ready to tackle the ~~CP~~ measurement

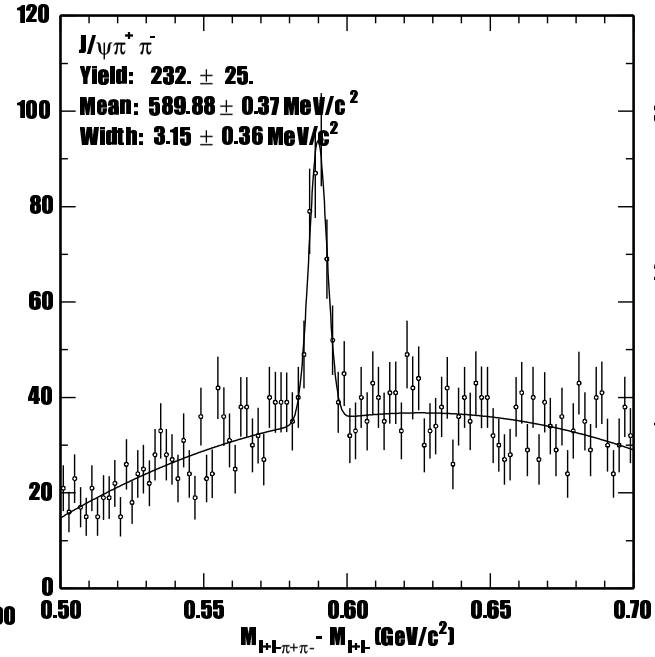
Reconstructing the CP Eigenstates

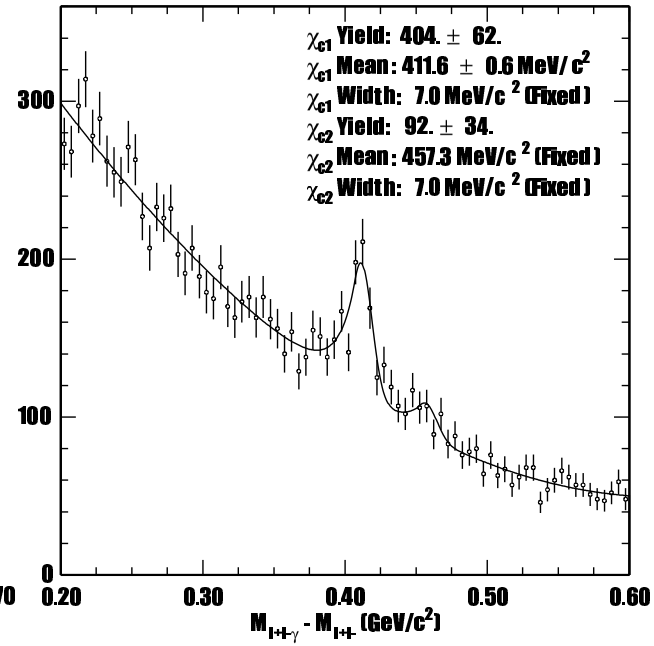
- To measure CP violation we must reconstruct as many B decays into CP eigenstates as possible with good signal to noise ratio
  - $J/\psi K_S$, $J/\psi \to l^+l^-$
    - $K_s \to \pi^+\pi^-$
    - $K_s \to \pi^o\pi^o$
  - $\psi' K_S$, $K_S \to \pi^+\pi^-$
    - $\psi' \to J/\psi \pi^+\pi^-$
    - $\psi' \to l^+l^-$
  - $\chi_{c1} K_S$, $\chi_{c1} \to \gamma J/\psi$, $K_S \to \pi^+\pi^-$
  - $J/\psi \pi^o$, $J/\psi \to l^+l^-$
  - $J/\psi K_L$, $J/\psi \to l^+l^-$
    - We can only measure the direction of K_L, not energy

Inclusive ψ' and χ_{c1} Signals

- We require the tight lepton identification to both lepton tracks
  - P*<1.7GeV/c
  - Dilepton mass >0.4GeV/c^2
  - P*<1.7GeV/c
  - E_γ>60MeV
  - Monte Carlo line shape

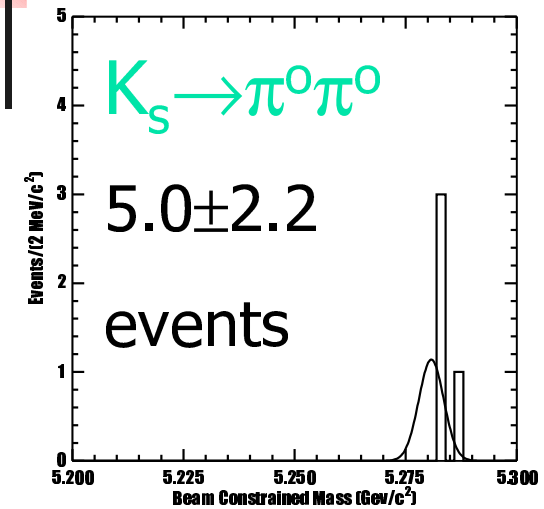


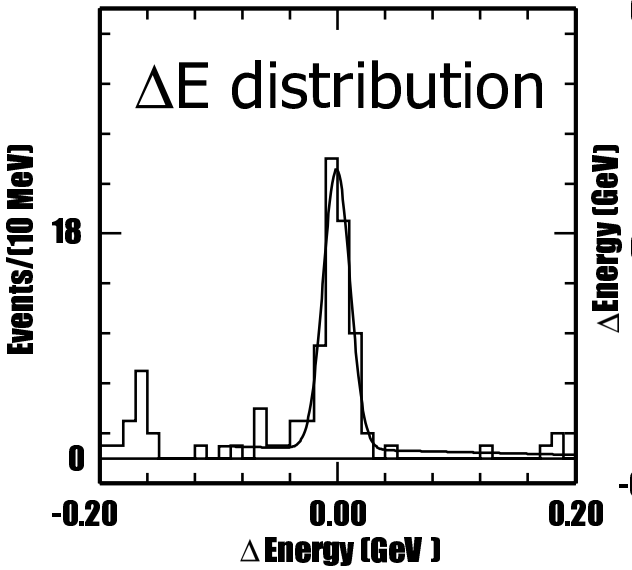


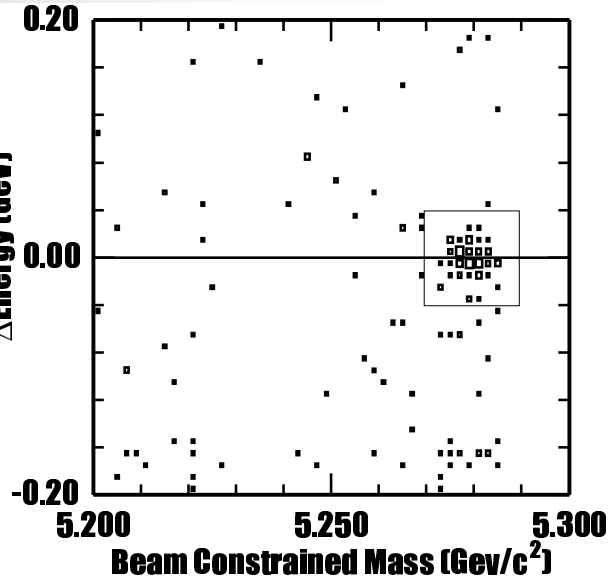


$J/\psi K_S$ Events

ΔE vs M_b



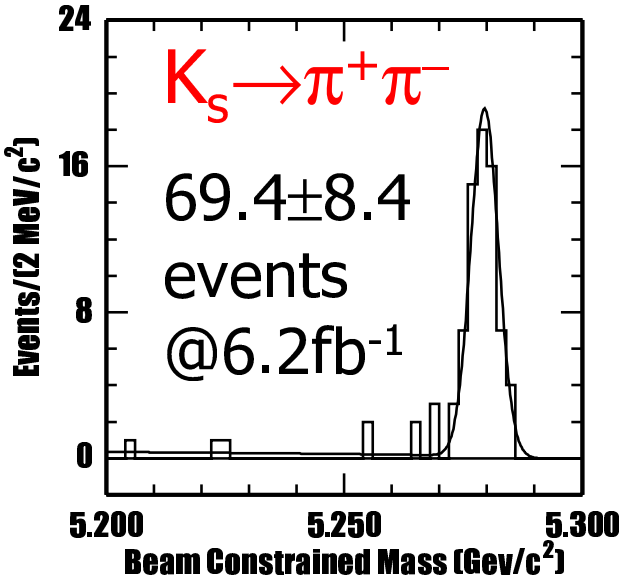




- Use beam constrained mass, M_b and ΔE:

$$M_b = \sqrt{E_{beam}{}^2 - p_B^2}, \quad \Delta E = E_B - E_{beam}$$

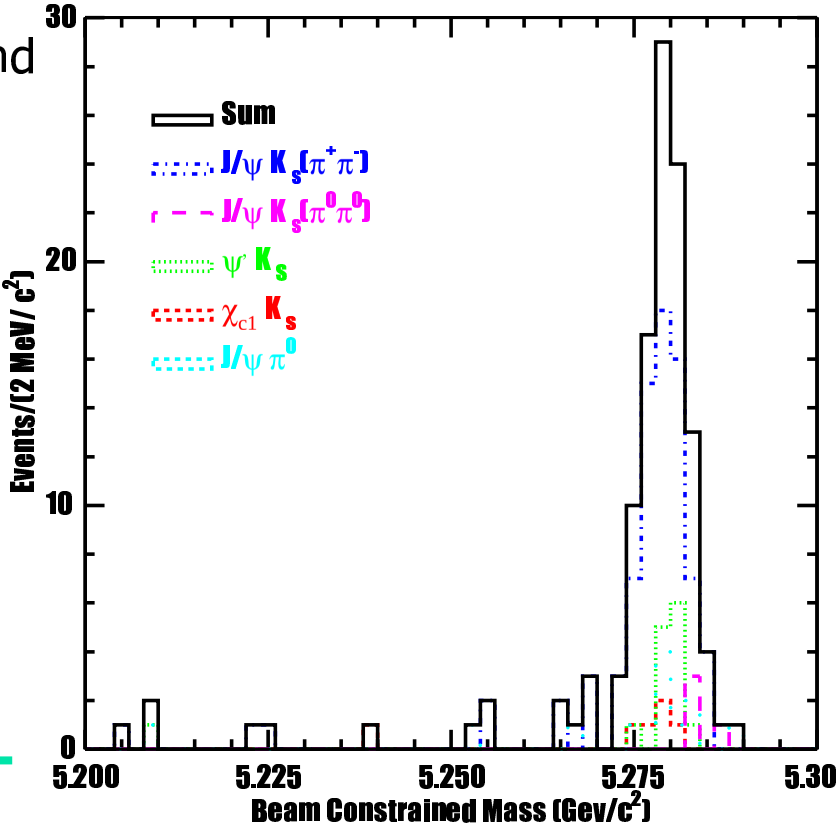
- $K_s \to \pi^+\pi^-$ ⇒⇒⇒⇒⇒⇒⇒⇒⇒⇒
- $K_s \to \pi^o\pi^o$ ⇑⇑⇑



CP Eigenstates Reconstructed

Note:$J/\psi K_L$ will be discussed separately

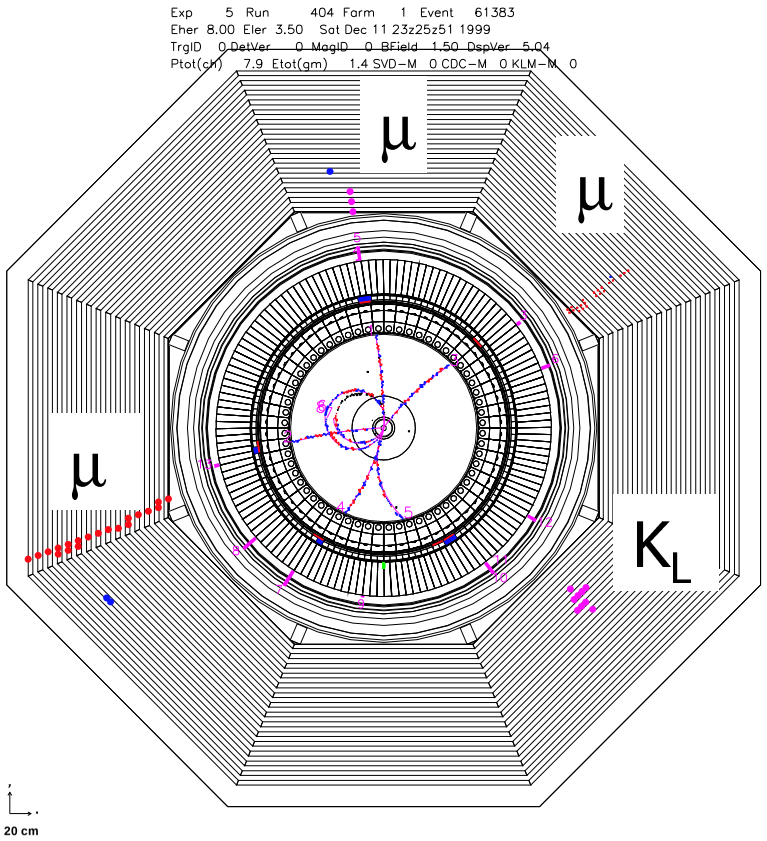
CP eigenstates	cand.	background
$J/\psi K_S$, $J/\psi \to l^+l^-$		
$K_s \to \pi^+\pi^-$	70	3.4
$K_s \to \pi^o\pi^o$	4	0.3
$\psi' K_S$, $K_S \to \pi^+\pi^-$		
$\psi' \to J/\psi\pi^+\pi^-$	8	0.6
$\psi' \to l^+l^-$	5	0.2
$\chi_{c1} K_S$, $\chi_{c1} \to \gamma J/\psi$	5	0.75
$J/\psi\pi^o$, $J/\psi \to l^+l^-$	10	1
Total	102	6.25

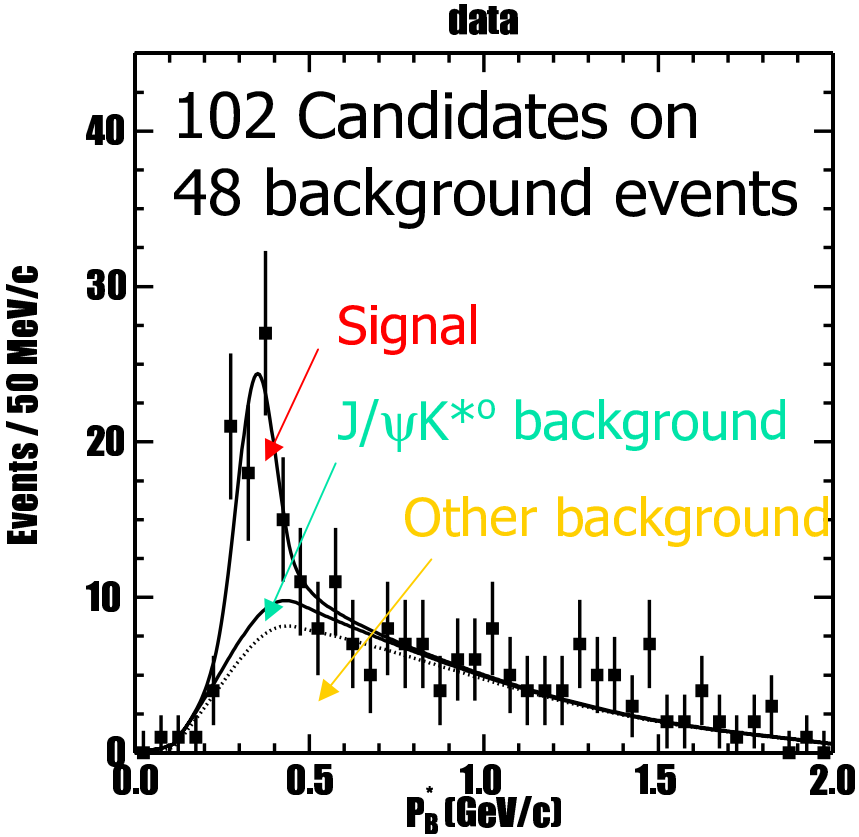


Note:We should not have used $J/\psi\pi^o$ mode but we did anyway…

J/ψ K_L Reconstruction

- K_L detection:direction only. Do a 0c fit and plot the absolute momentum of B in the CM frame, which peaks at 0.34GeV/c



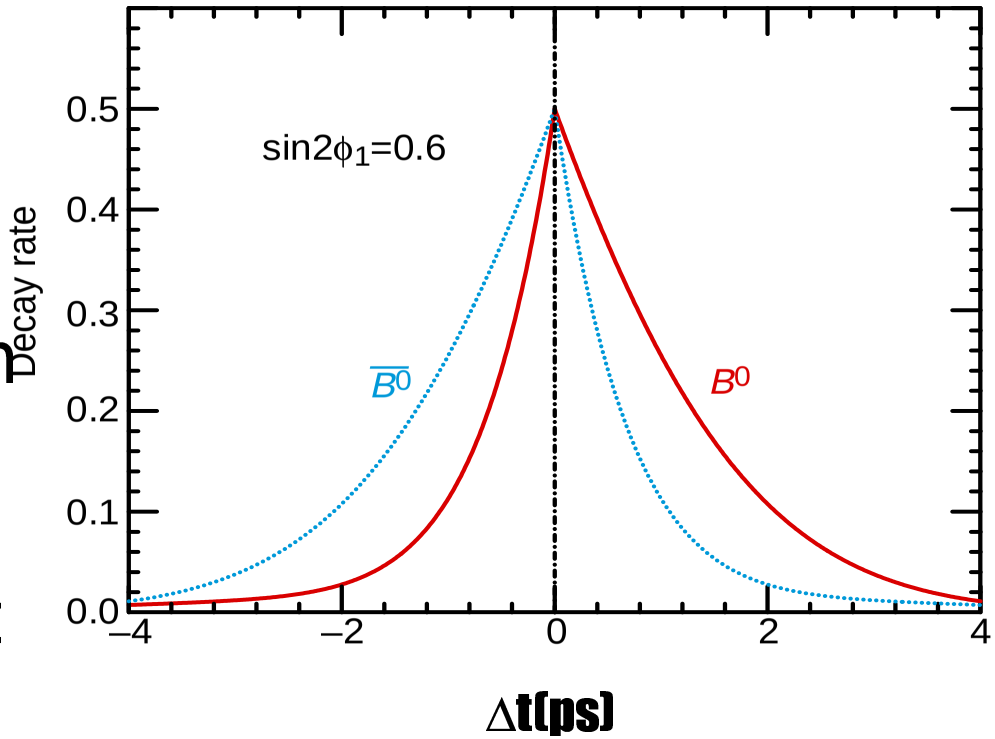


Summary of CP Analysis (so far)

- Reconstruction of CP eigenstates (before tag)
  - 102 charmonium+K_s and $J/\psi\pi^o$ candidates (6.25 est. bg)
  - 102 $J/\psi K_L$ candidates (48 est. bg)
- Flavor tagging
  - Lepton and Kaon tag (w determined with $D^{(*)}l\nu$)
  - Slow momentum pion and mid. momentum/missing momentum tags are also used. w determined by MC
- Vertex tagging and resolution function
  - Simple algorithm rejecting badly measured tracks
  - Sigmas determined with MC and continuum D mesons
  - The same technique is used in the B lifetime measurements

Maximum Likelihood Fit

- The asymmetry, $A(\Delta t)$ is proportional to $\sin(\Delta m_d \Delta t)$
- The resolution function must be convoluted
- Use unbinned maximum likelihood fit with event by event



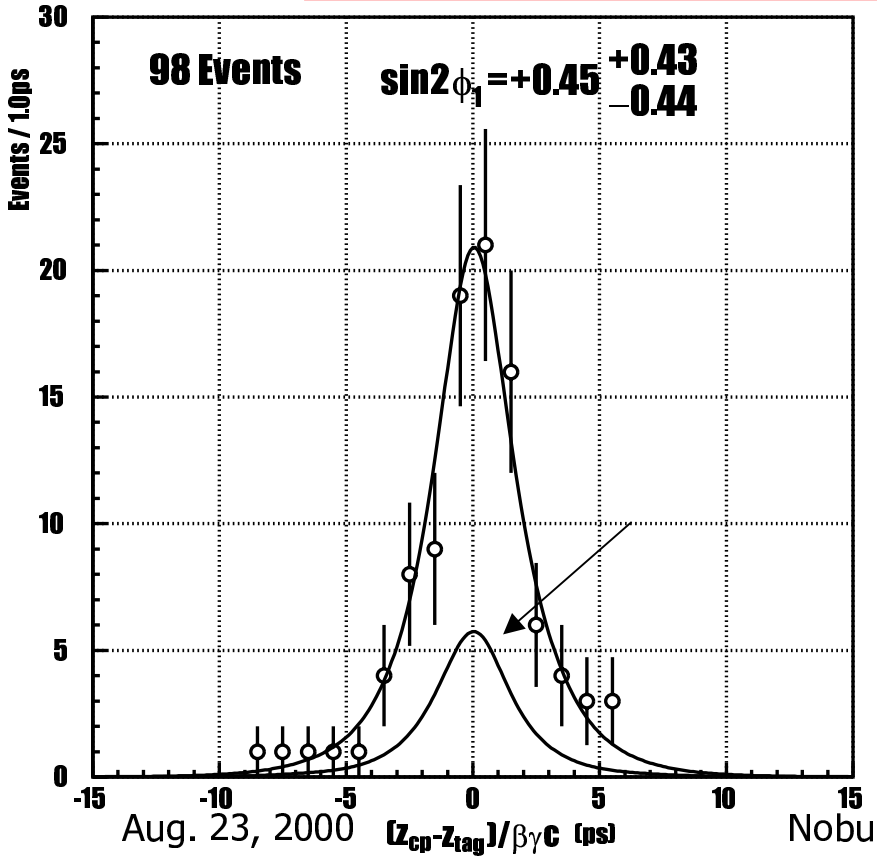
  - resolution function (as a function of measured σs)
  - background fraction (as a function of ΔE, M_b)
  - wrong sign fraction (as a function of the tag type)

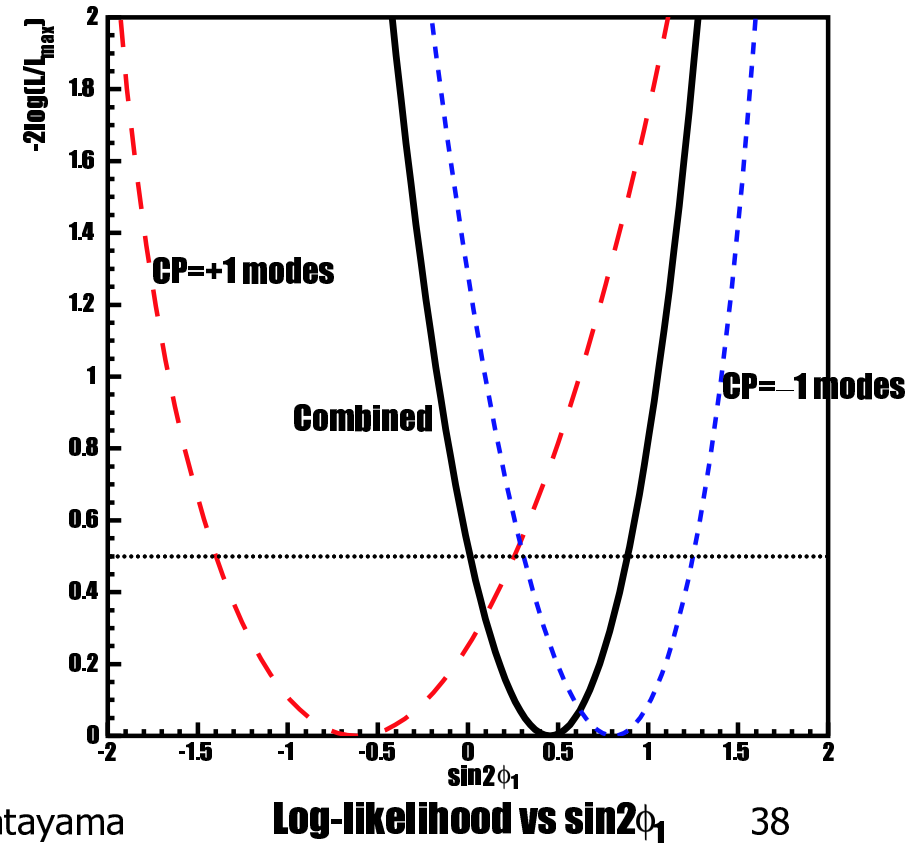
to obtain the CP parameter, $\sin(2\phi_1)$

Fit Result

- Using 98 events tagged out of 102+102 sample we obtain the value of $\sin(2\phi_1)$ to be $+0.45^{+0.43}_{-0.44}(stat.)^{+0.07}_{-0.09}(syst.)$

Belle Preliminary

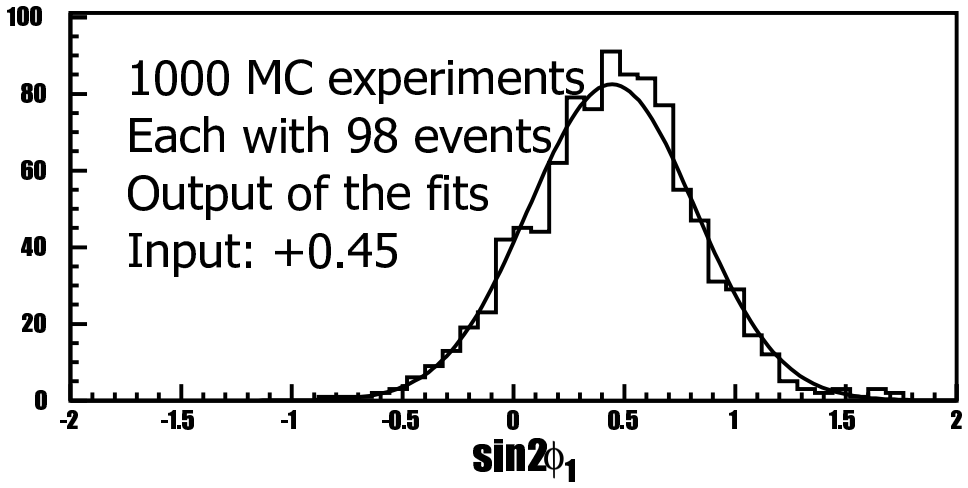


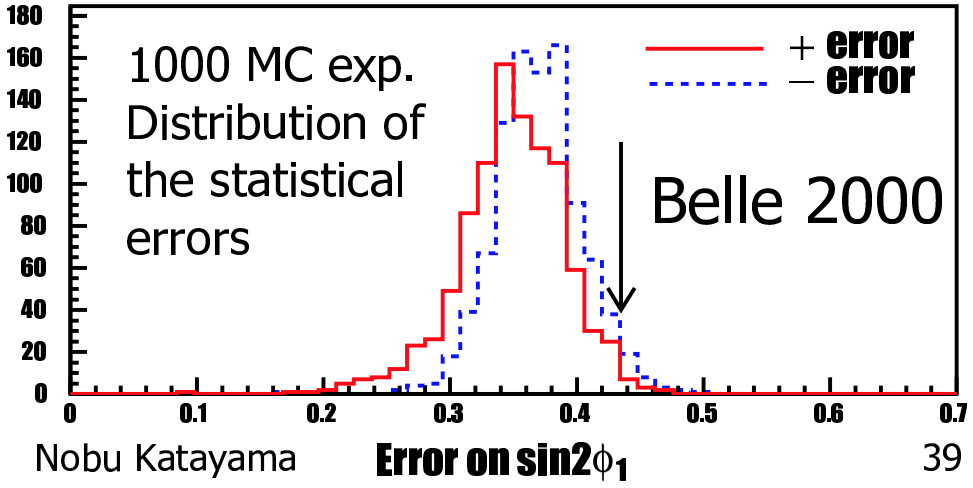


Log-likelihood vs $\sin2\phi_1$

Statistical Error

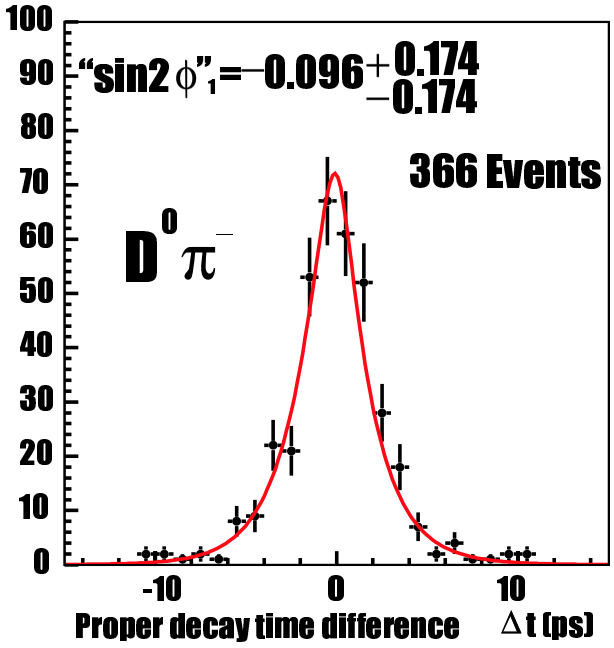
- Previously, the statistical error on $\sin(2\phi_1)$ has been estimated using Monte Carlo events with high statistics and then scaled
- We now use toy experiments with the event size 98 and obtain the distribution of statistical errors
- As seen we were unlucky or the likelihood is not parabolic or something else

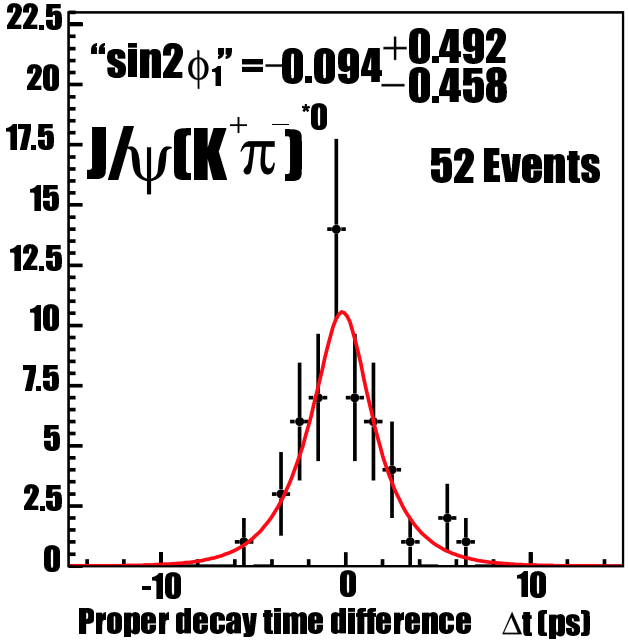


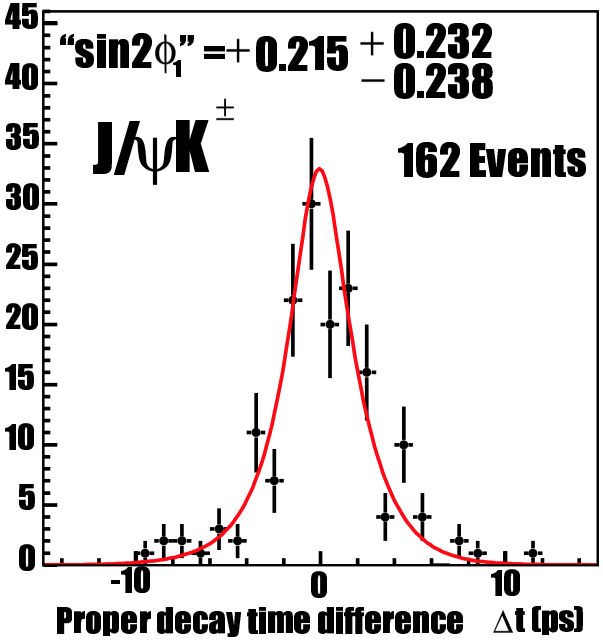


Control Samples

- We do have various control samples which should have no asymmetry
  - ⇨None of the samples, including untagged CP eigenstates sample showed asymmetry that is not consistent with 0







Systematic Errors

Source	$\sigma+$	$\sigma-$
Wrong tag fraction	+0.0495	–0.0660
Resolution function	+0.0264	–0.0246
Background res. function	+0.0292	–0.0421
Background fraction/shape	+0.0291	–0.0323
τ_B, Δm_d	+0.0054	–0.0056
Interaction point profile	+0.0041	0.0
Total	+0.0699	–0.0884

Conclusions

- KEKB and Belle have had a successful first run from Oct. '99 to July 2000
  - We accumulated 6.2 fb^{-1} on the Y(4S) peak
- With all the data accumulated we obtained

$$\sin(2\phi_1) = +0.45^{+0.43}_{-0.44}(stat.)^{+0.07}_{-0.09}(syst.)$$

Belle $$\tau(B^o) = 1.50 \pm 0.05 \pm 0.07\, ps$$

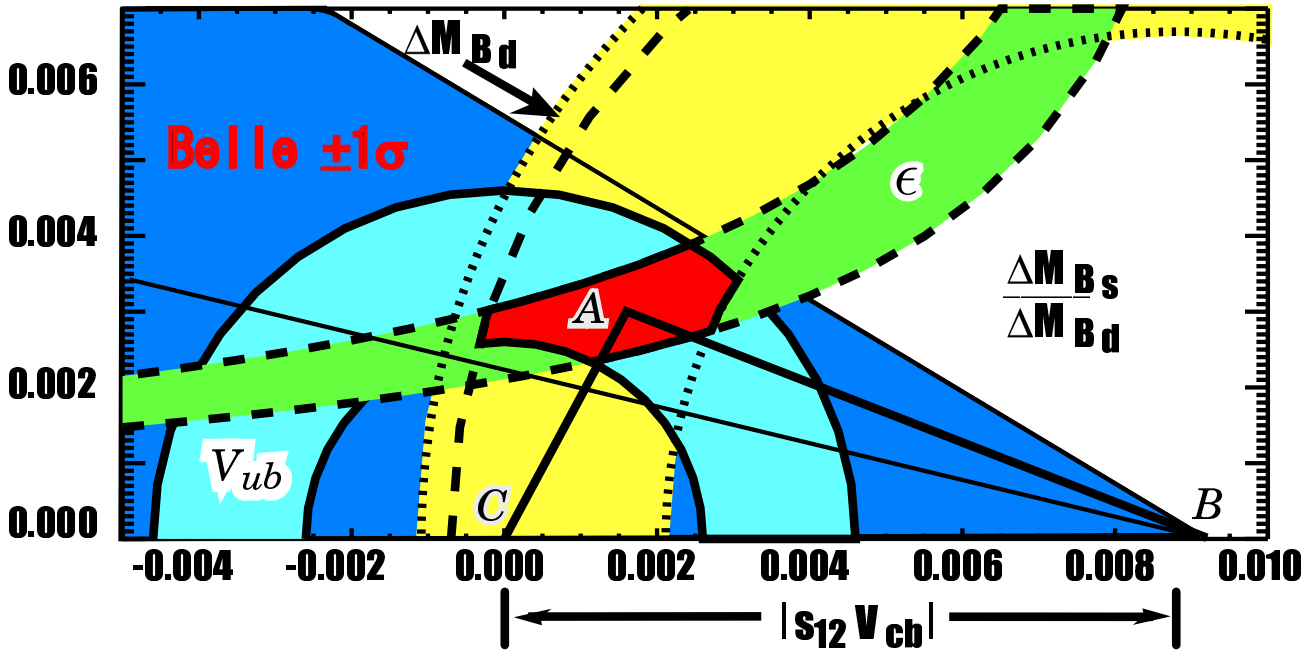
Preliminary $$\tau(B^+) = 1.70 \pm 0.06^{+0.11}_{-0.10}\, ps$$

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

- Other physics results are reported at the ICHEP2000 and papers are on the way

CKM Matrix Constrained…

- We need a lot more statistics to actually become useful
- Hope to get a lot more data in coming years



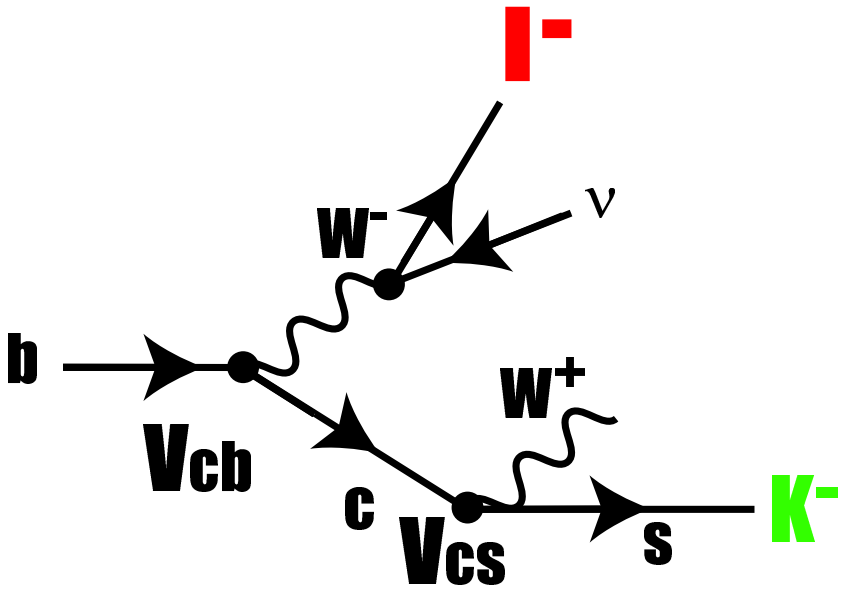
KEKB / Belle Prospects

- We have installed a radiation hard (~1Mrad) SVD
- Improvements of KEKB components
  - Better movable masks
  - More RF power (HER1.1A, LER1.6A)
  - Solenoidal field on the LER beam pipe to remove photo-electron cloud
- We resume the data taking from mid. October
- We hope to achieve ~$4\times10^{33}cm^{-1}s^{-1}$ this fall and take 4–$5fb^{-1}$ per month through July 2001
- Further upgrades of the KEKB and Belle are under discussion/study

Flavor Tagging with Belle

- Lepton from B semileptonic decays
- Charged Kaon from subsequent charm decays

	Effic.(%)	Wrong tag. Frac(%)	Effect. tag. Effic.(%)
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
Mid lep	2.8(MC)	29.5(MC)	0.50(MC)
Slow π	7.0(MC)	34.0(MC)	0.71(MC)



- $B \rightarrow D^{*-}$ decays (slow pions)

CP Eigenstates Tagged

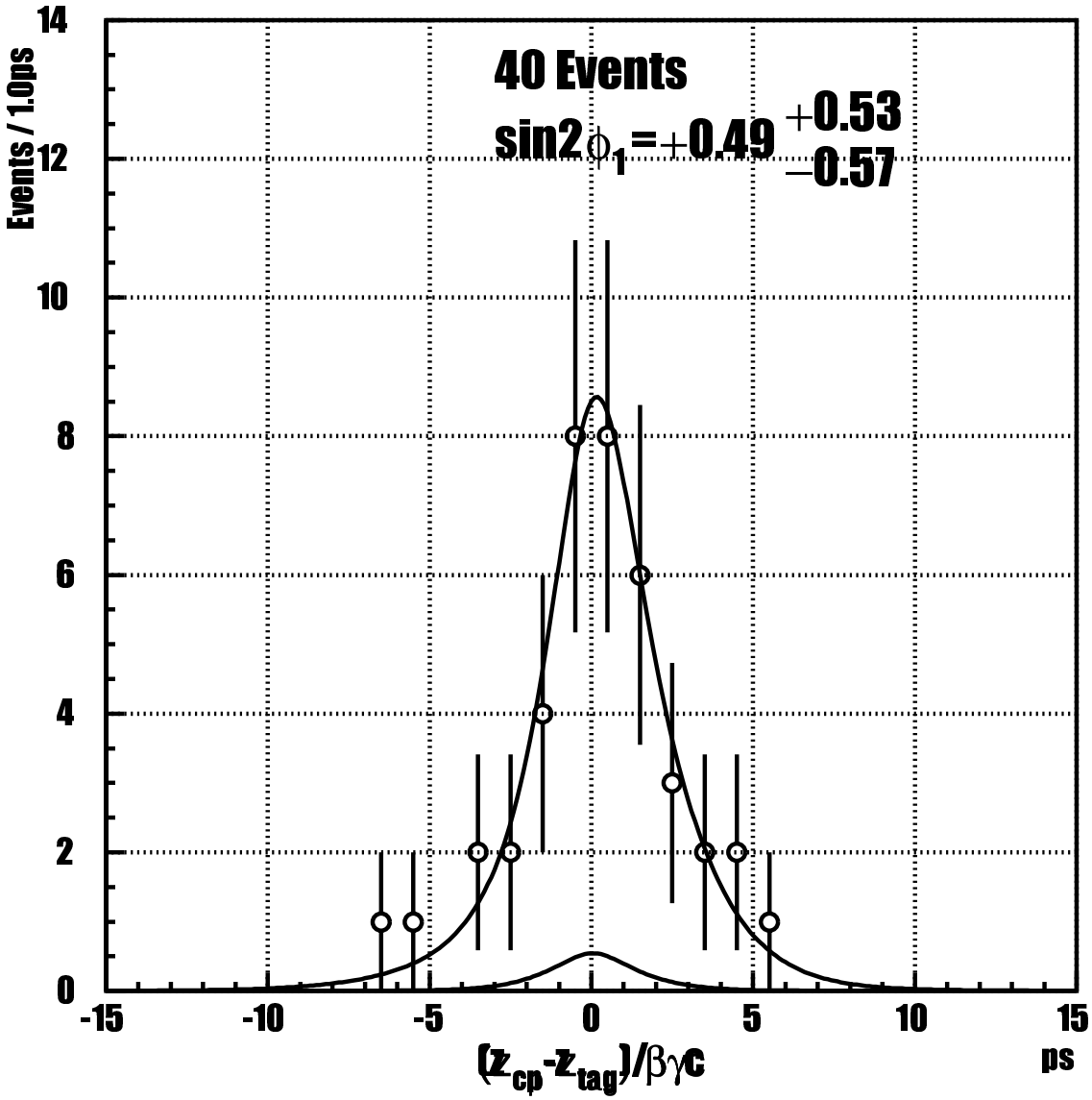
CP eigenstates	cand.	Background	Tagged
$J/\psi K_S$, $J/\psi \to l^+l^-$			
$K_s \to \pi^+\pi^-$	70	3.4	40
$K_s \to \pi^o\pi^o$	4	0.3	4
$\psi' K_S$, $K_S \to \pi^+\pi^-$			
$\psi' \to J/\psi\pi^+\pi^-$	8	0.6	3
$\psi' \to l^+l^-$	5	0.2	2
$\chi_{c1} K_S$, $\chi_{c1} \to \gamma J/\psi$	5	0.75	3
$J/\psi\pi^o$, $J/\psi \to l^+l^-$	10	1	4
$J/\psi K_S$, $J/\psi \to l^+l^-$	102	48	42
Total	204	54.25	98

Tag	e	μ	K	e_{mid}	μ_{mid}	π_{soft}	Total
	14	12	48	3	3	18	98

Fit result ($J/\psi K_s$, $K_s \to \pi^+\pi^-$ only)

- 40 tagged out of 70 J/ψKs , $K_s \to \pi^+\pi^-$ events

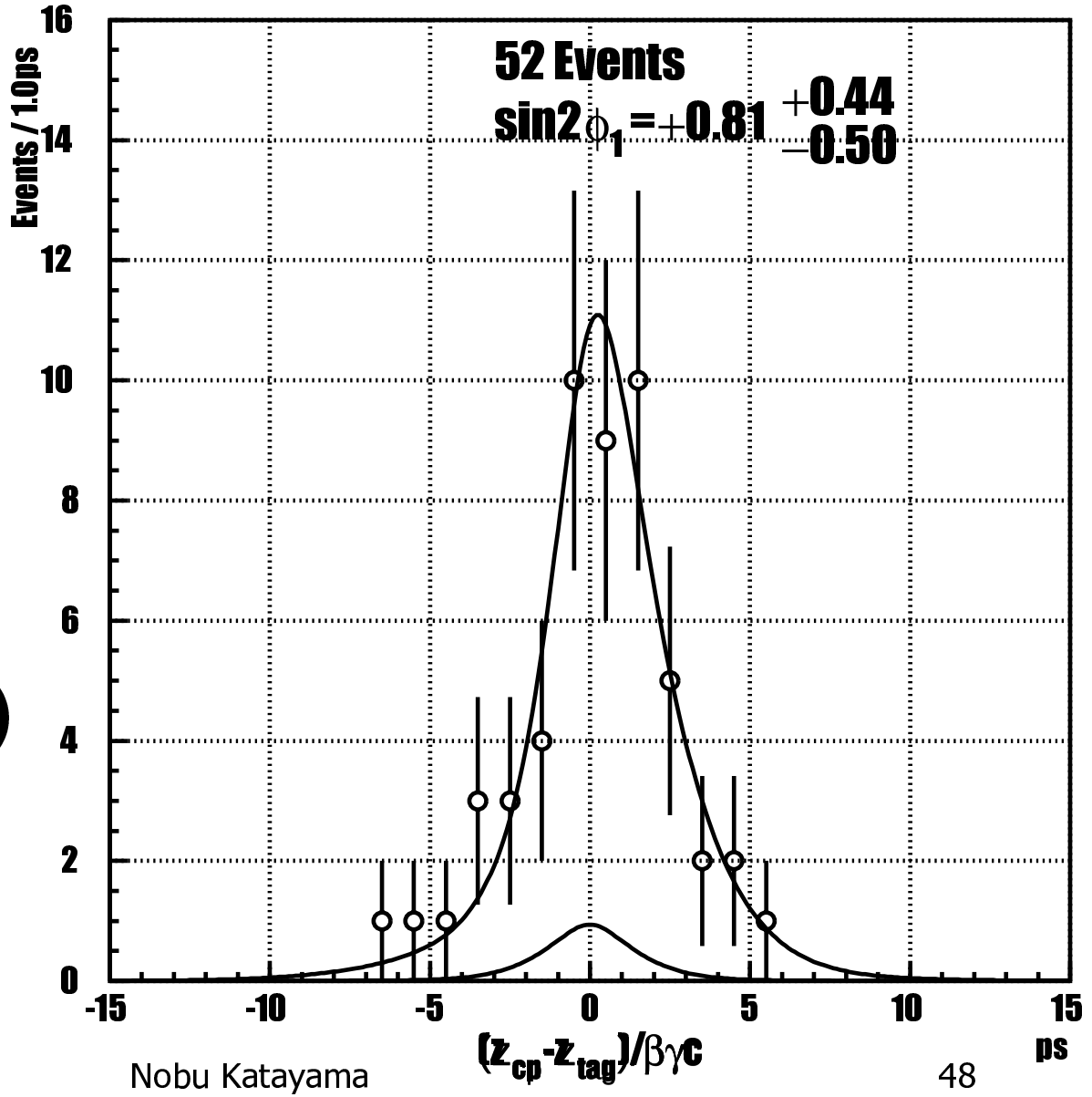
$$\sin(2\phi_1) = +0.49^{+0.53}_{-0.57}(stat.)$$



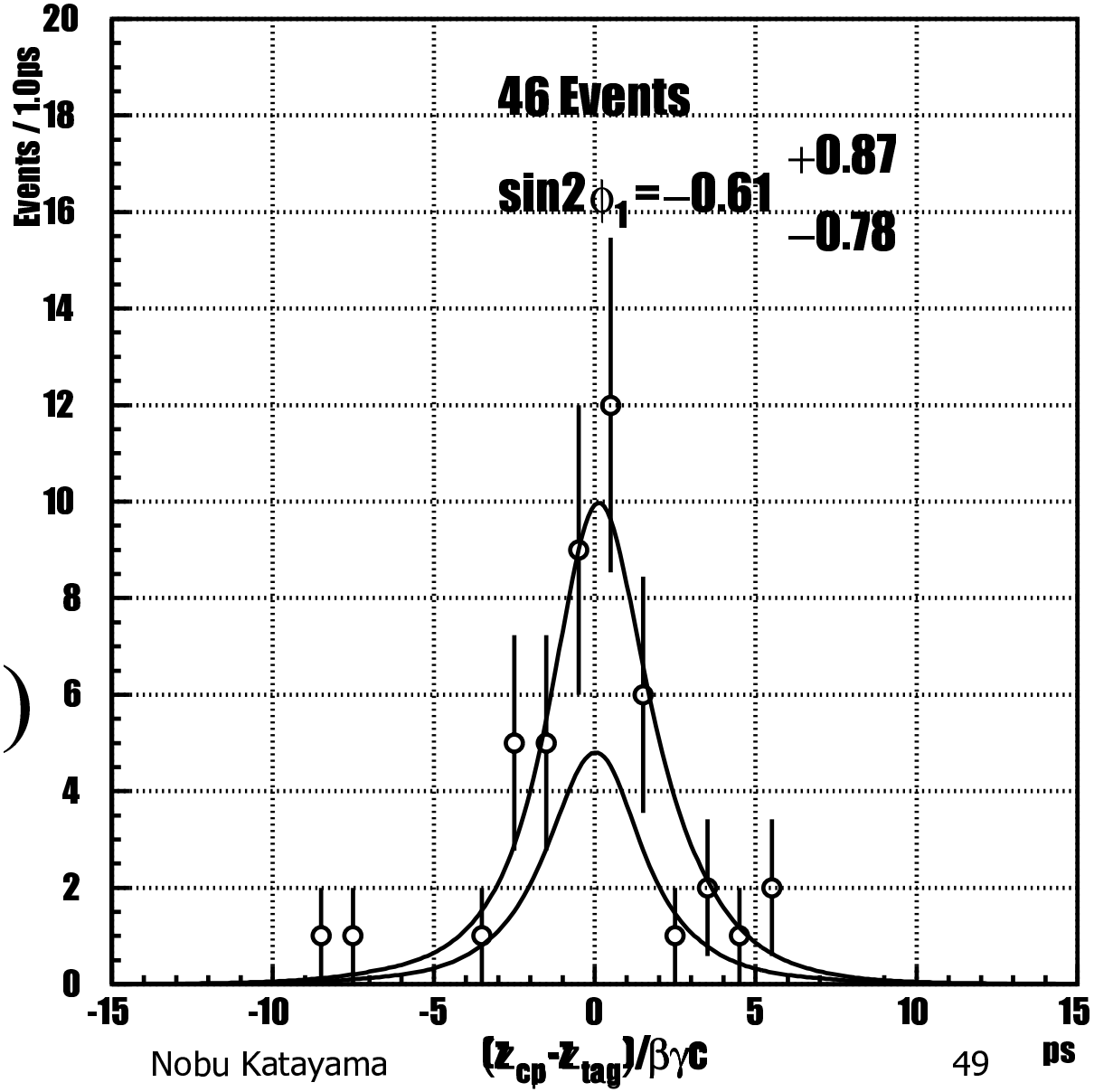
Fit result (All CP=−1 modes)

- 52 tagged events out of 92 events

$$\sin(2\phi_1) = +0.81^{+0.44}_{-0.50}(stat.)$$



Fit result (All CP=+1 modes)

- 46 tagged events out of 112 events

$$\sin(2\phi_1) = -0.61^{+0.87}_{-0.78}(stat.)$$