CP Violation in the B Meson System: The Belle Measurement of $sin2\phi_1$

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for the

BELLE Collaboration

The BELLE Collaboration

≈300 people from 49 Institutions in 11 Countries:

Australia, China, India, Korea, Japan, Philippines, Poland, Russia, Taiwan, Ukraine, and USA

Academia Sinica	Aomori University
Budker Inst. of Nuclear Physics	Chiba University
Chuo University	University of Cincinatti
Fukui University	GyeongSang National University
University of Hawaii	Institute of High Energy Physics
Institute of Single Crystal	Joint Crystal Collab. Group
Kanagawa University	KEK
Korea University	Krakow Inst. of Nuclear Physics
Kyoto University	Melbourne University
Mindanao State University	Nagasaki Inst. of App. Science
Nagoya University	Nara Women's University
National Lien Ho Colledge of T&C	National Taiwan University
Nihon Dental College	Niigata University
Osaka University	Osaka City University
Princeton University	Saga University
Sankyun Kwan University	Univ. of Science & Technology of China
Seoul National University	Sugiyama Jyogakuin University
University of Sydeny	Toho University
Tohoku University	Tohoku-Gakuin University
University of Tokyo	Tokyo Metropolitan University
Tokyo Institute of Technology	Tokyo Univ. of Agricult. & Tech.
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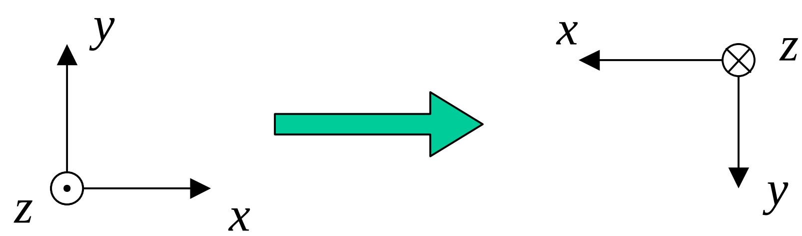
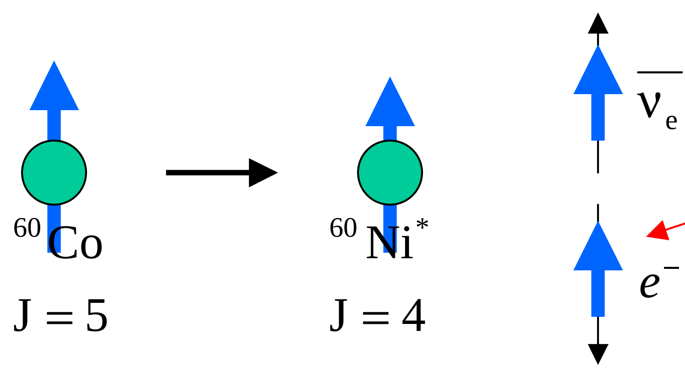
Parity Violation



- The "parity" operation transforms the universe into its mirror image (*goes from right-handed to left-handed*).
- Maxwell's equations are totally parity invariant.
- BUT, in the 50's huge parity violation was observed in weak decays…

β decay of polarized **Co:**



electron preferentially emitted opposite spin direction

CP *(almost)* Conservation

- It was found that by applying the **C**[harge Conjugation] operation to all particles, the overall symmetry seemed to be restored (neutrinos are left-handed, anti-neutrinos are right-handed).
- This symmetry fit nicely into the current algebras, and later the gauge theories being used to describe weak interactions.
- Unfortunately, it wasn't *quite* exact…

CP Violation

- In 1964, Fitch, Cronin, *etal*, showed that physics is not *quite* invariant under the CP operation, essentially by proving that neutral kaons formed mass eigenstates

$$\left|K_{L,S}\right\rangle \equiv a_{L,S}\left|K^0\right\rangle + b_{L,S}\left|\overline{K^0}\right\rangle \quad \text{where} \quad \left|a_{L,S}\right| \neq \left|b_{L,S}\right|$$

- This generated great interest (not to mention a Nobel Prize), and has been studied in great detail ever since, but to date has only been conclusively observed in the kaon system.

$$\left(\left|a_{L,S}\right| - \left|b_{L,S}\right| \approx O(10^{-3})\right)$$

Quark Mixing

$$\begin{pmatrix} \nu_e \\ \updownarrow \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \updownarrow \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \updownarrow \\ \tau^- \end{pmatrix}$$

Leptons can only transition *within* a generation

$$\begin{pmatrix} u \\ \updownarrow \\ d \end{pmatrix} \begin{pmatrix} c \\ \updownarrow \\ s \end{pmatrix} \begin{pmatrix} t \\ \updownarrow \\ b \end{pmatrix}$$

Although the rate is *suppressed*, quarks can transition *between* generations.

The CKM Matrix

- The weak quark eigenstates are related to the strong (or mass) eigenstates through a unitary transformation.

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \Rightarrow \begin{pmatrix} u \\ \updownarrow \\ d' \end{pmatrix} \begin{pmatrix} c \\ \updownarrow \\ s' \end{pmatrix} \begin{pmatrix} t \\ \updownarrow \\ b' \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- The only straightforward way to *accommodate* CP violation in the SM is by means of an irreducible phase in this matrix (requires at least three generations, led to prediction of *t* and *b* quarks)

Wolfenstein Parameterization

The CKM matrix is an SU(3) transformation, which has four free parameters. Because of the scale of the elements, this is often represented with the "Wolfenstein Parameterization"

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

First two generations *almost* unitary.

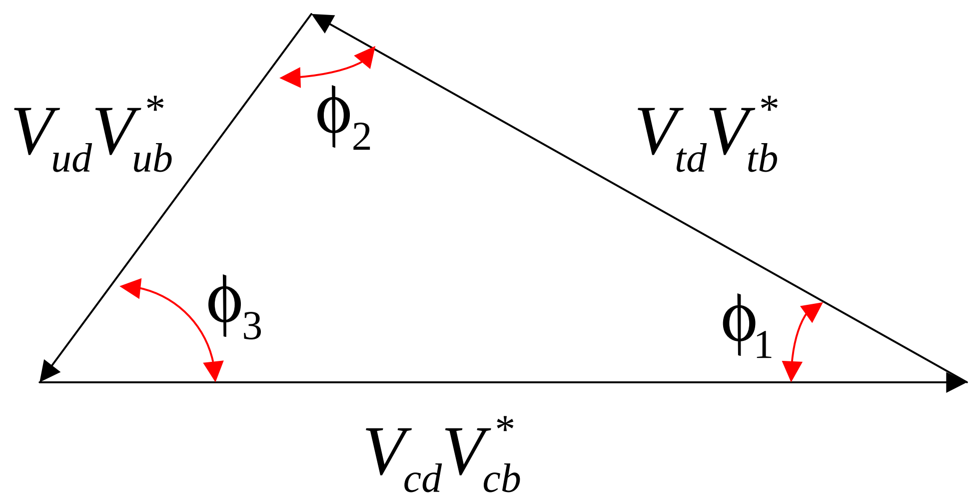
CP Violating phase

"The" Unitarity Triangle

- Unitarity imposes several constraints on the matrix, but one...

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

Results in a triangle in the complex plane with sides of similar length $\left(\approx A\lambda^3\right)$, which appears the most interesting for study



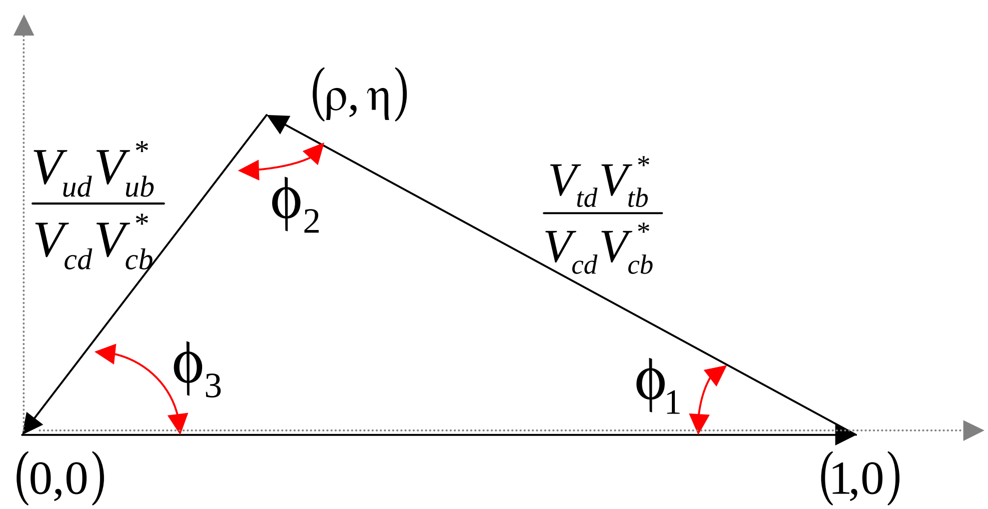
$$(\text{Note! in US}: \ \phi_1 \equiv \beta, \ \phi_2 \equiv \alpha, \ \phi_3 \equiv \gamma)$$

The ρ–η Plane

- Remembering the Wolfenstein Parameterization

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

we can divide through by the magnitude of the base….



CP violation is generally discussed in terms of this plane

Direct CP Violation

- CP Violation is manifests itself as a difference between the physics of matter and anti-matter

$$\Gamma(i \Rightarrow f) \neq \Gamma(\bar{i} \Rightarrow \bar{f})$$

- *Direct* CP Violation is the observation of a difference between two such decay rates; however, the amplitude for one process can in general be written

$$A = |A| e^{i\phi_w} e^{i\phi_s} \Rightarrow \bar{A} = |A| e^{-i\phi_w} e^{i\phi_s}$$

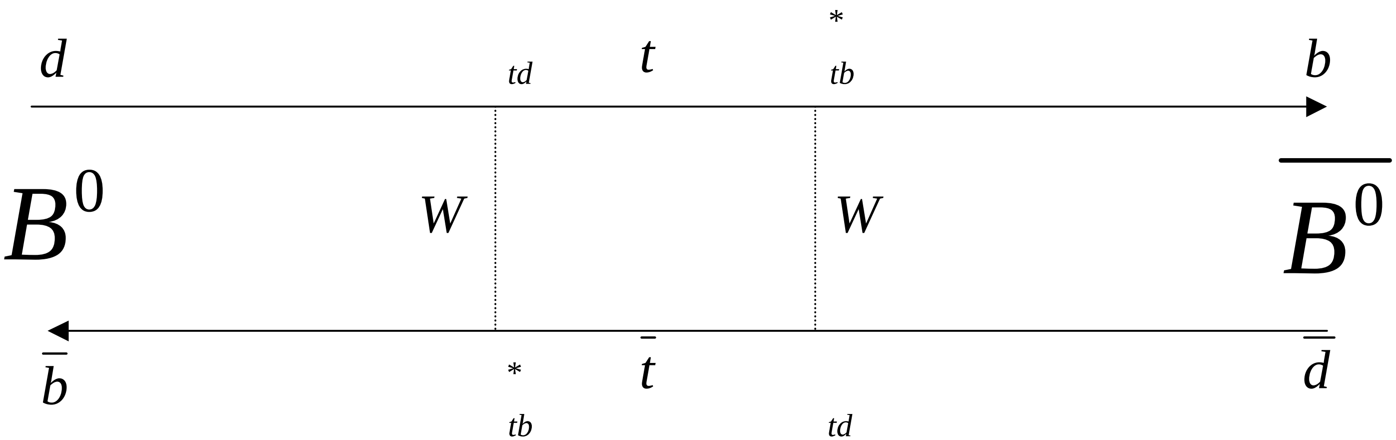
Weak phase changes sign   Strong phase does not

- Since the observed rate is only proportional to the amplitude, a difference would only be observed if there were an *interference* between two diagrams with different weak *and* strong phase.

$\Rightarrow$ Rare and hard to interpret

Indirect CP Violation

- Consider the case of B-mixing

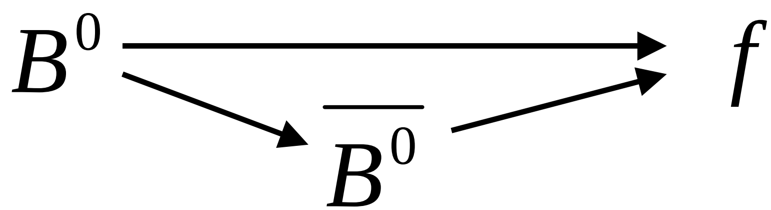


$$\left|B^0(t)\right\rangle = e^{-i(m-i\Gamma)/2} \times \left[\cos\left(\frac{\Delta mt}{2}\right)\left|B^0\right\rangle + i\sin\left(\frac{\Delta mt}{2}\right)e^{-2i\phi_m}\left|\overline{B}^0\right\rangle\right]$$

Mixing phase $= \arg(V_{td}V_{tb}^*) = \phi_1$

Indirect CP Violation (cont'd)

- If both B and $\overline{B}$ can decay to the same *CP eigenstate* f, there will be an *interference*



And a time-dependent asymmetry

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0 \to f) - \Gamma(\overline{B}^0 \to f)}{\Gamma(B^0 \to f) + \Gamma(\overline{B}^0 \to f)}$$

$$= -2\eta_f \sin(\Delta m \Delta t) \sin 2(\phi_M + \phi_D)$$

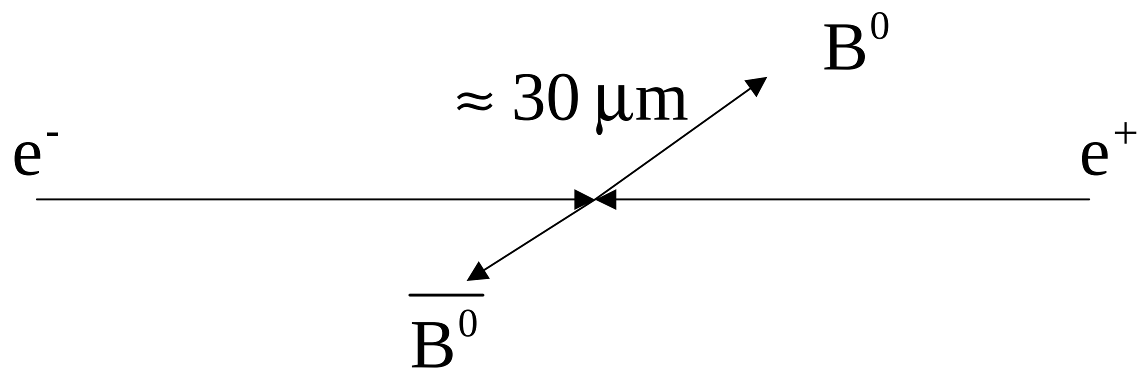
Decay phase

CP state of f

Mixing phase

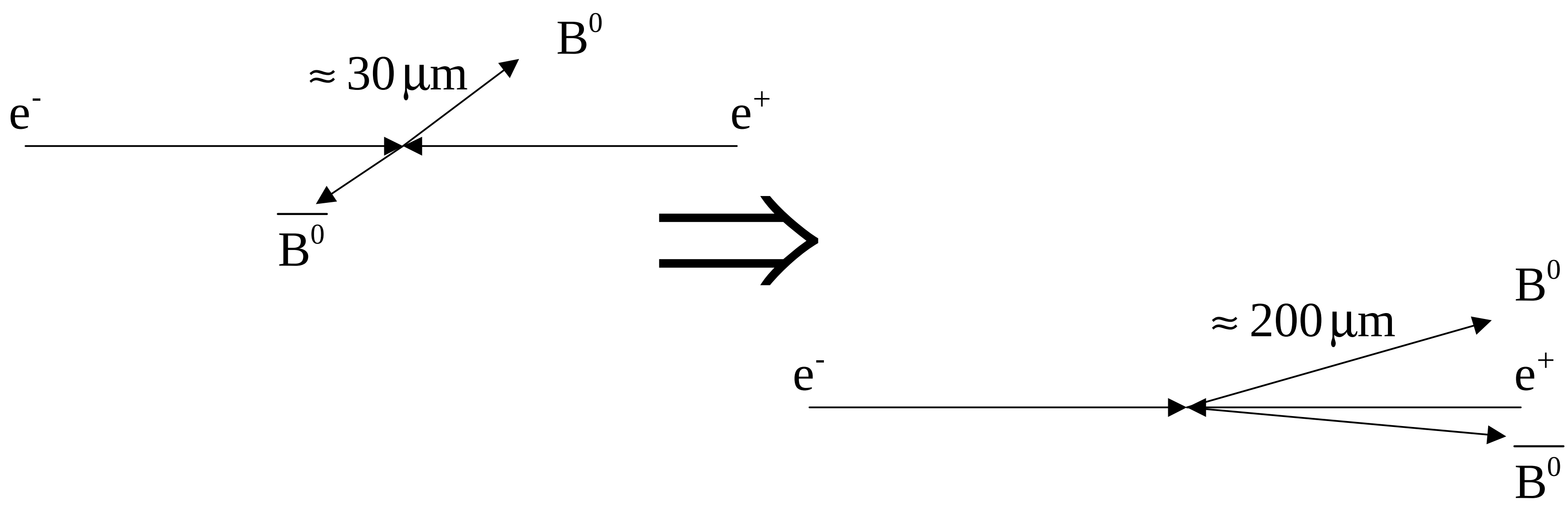
The Basic Idea

- We can create $B^0\overline{B^0}$ pairs at the $\Upsilon(4S)$ resonance.
- Even though both *B*'s are mixing, if we tag the decay of one of them, the other must be the CP conjugate *at that time*. We therefore measure the time dependent decay of one B relative to the time that the first one was tagged (EPR "paradox").
- PROBLEM: At the $\Upsilon(4S)$ resonance, B's only go about 30 μm in the center of mass, making it difficult to measure time-dependent mixing.

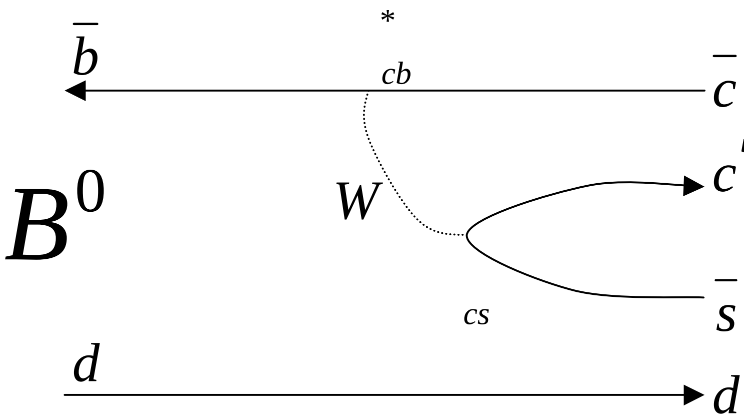


The Clever Trick

- If the collider is *asymmetric*, then the entire system is Lorentz boosted.
- In the Belle Experiment, 8 GeV e^-'s are collided with 3.5 GeV e^+'s so



- So now the time measurement becomes a *z* position measurement.



$$J/\psi \quad (\psi \to e^+e^-, \mu^+\mu^-, \text{ etc})$$

Total state CP

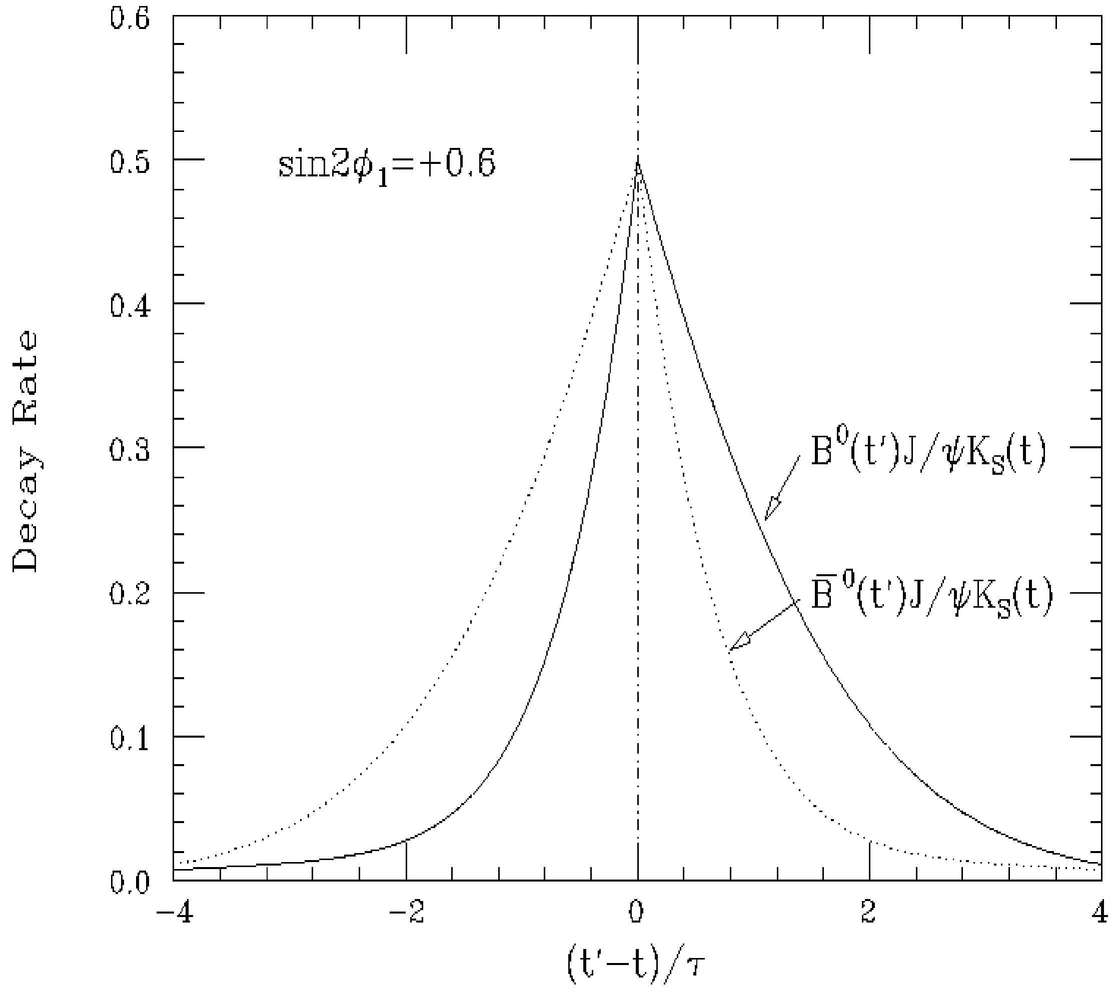
$$K_S(CP = -1), K_L(CP = +1)$$

$$\hookrightarrow \pi^+\pi^-, \pi^0\pi^0$$

$$\phi_D = \arg(V_{cs}V_{cb}^*) \approx 0$$

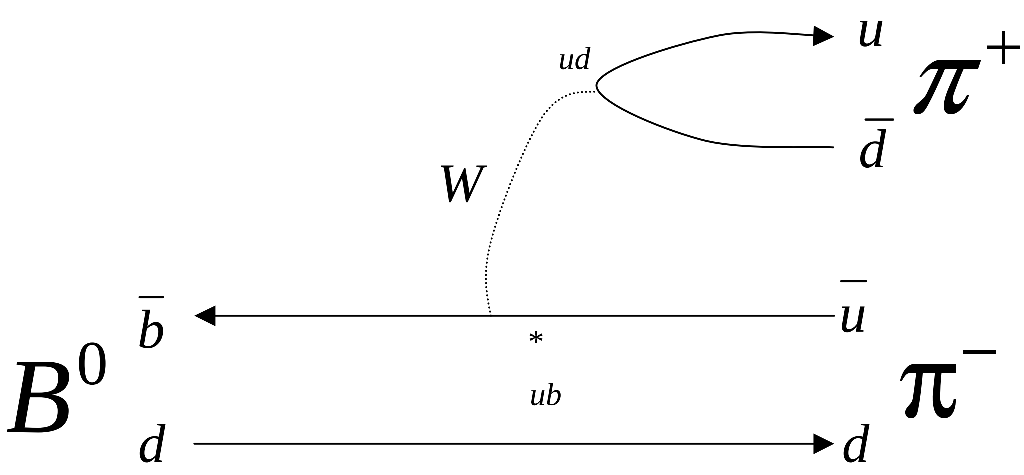
$$\text{probes } \phi_M = \phi_1 \ (= \beta)$$

Predicted Signature



t = Time of tagged decays

“Tin-Plated” Decay



$$\phi_D = \arg(V_{ud} V_{ub}^*) \approx -(\phi_1 + \phi_2)$$

probes $\phi_M + \phi_D = \phi_1 - (\phi_2 + \phi_1) = -\phi_2 \ \ (= -\alpha)$

Complicated by “penguin pollution”, but still promising

What about ϕ_3?

- Corresponding decay would be $B_s \rightarrow \rho K_S$, but…
  - Require move to $\Upsilon(5s)$ resonance (messier)
  - Time dependent B_s mixing not possible.
- $\Rightarrow$ Have to find another way.

Review - What B-Factories Do...

- Make LOTS of $b\bar{b}$ pairs at the Υ(4S) resonance in an asymmetric collider.
- Detect the decay of one *B* to a CP eigenstate.
- Tag the flavor of the other *B*.
- Reconstruct the position of the two vertices.
- Measure the *z* separation between them and calculate proper time separation as $t = \Delta z / (\beta_{CM} \gamma_{CM} c)$
- Fit to the functional form

$$e^{-\Gamma|t|}\left[\left\{1 - \eta_{CP} \sin 2\phi_1 \sin \Delta m \Delta t\right\}\right]$$

- Write papers.

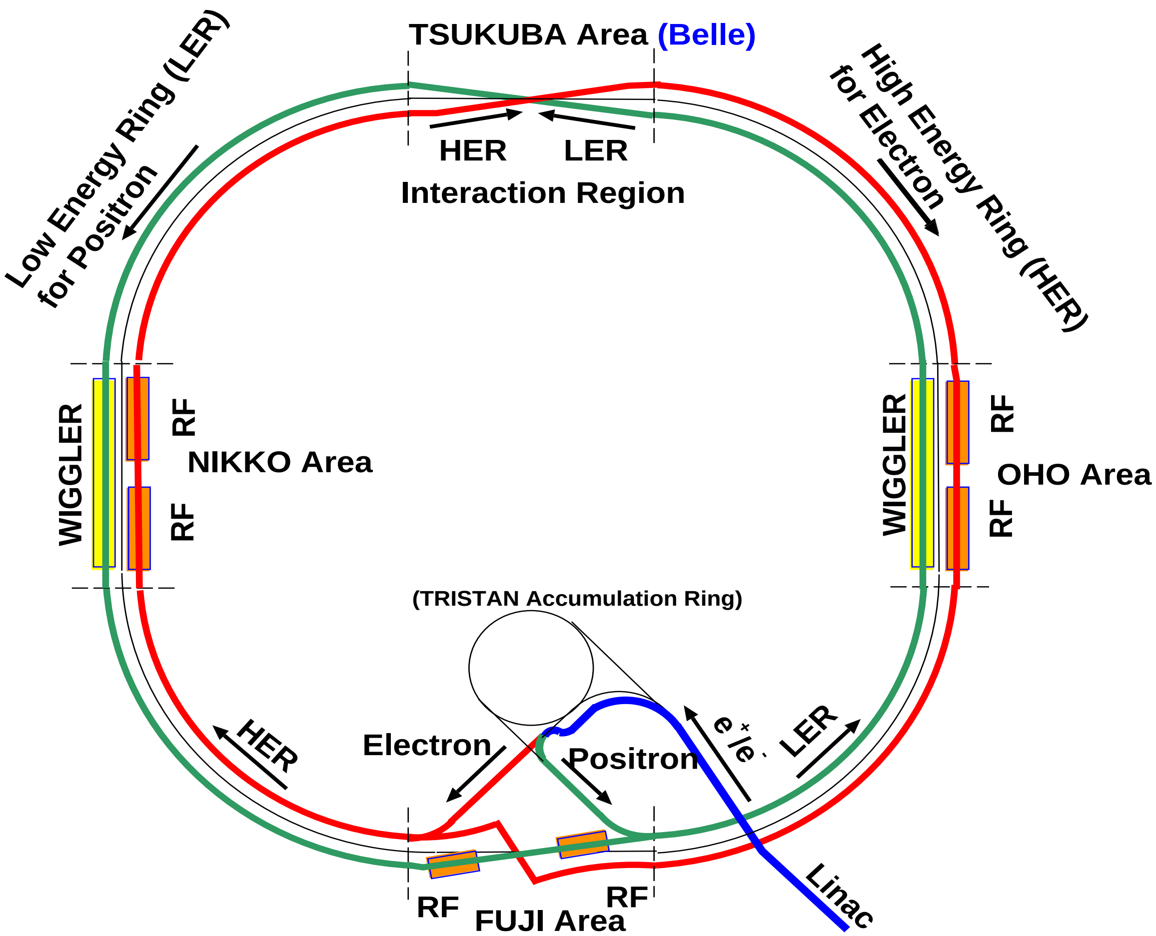
Are Two B-Factories Too Many?

- These are not discovery machines!
- Any interesting physics would manifest itself as small deviations from SM predictions.
- People would be very skeptical about such claims without independent confirmation.
- Therefore, the answer is NO (two is not *one* too many, anyway).

Motivations for Accelerator Parameters

- Must be asymmetric to take advantage of Lorentz boost.
- The decays of interest all have branching ratios on the order of 10^{-5} or lower.
  - Need lots and lots of data!
    - Physics projections assume $100\ fb^{-1} = 1yr\ @\ 10^{34}\ cm^{-2}s^{-1}$
    - Would have been pointless if less than $10^{33}\ cm^{-2}s^{-1}$

The KEKB Accelerator



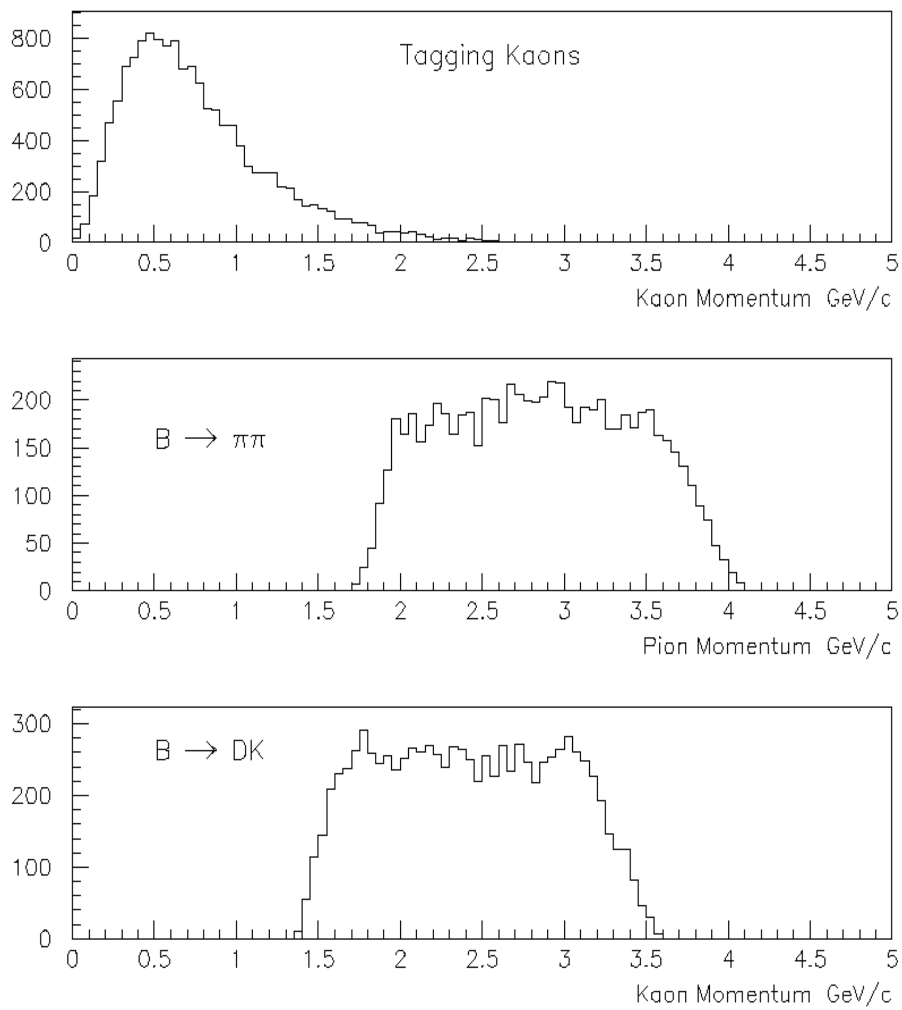
- Asymmetric Rings
  - 8.0GeV(HER)
  - 3.5GeV(LER)
- E_{cm}=10.58GeV= M(ϒ(4S))
- Target Luminosity: $10^{34}s^{-1}cm^{-2}$
- Circumference: 3016m
- Crossing angle: ±11mr
- RF Buckets: 5120
- ⇒ 2ns crossing time

Motivation for Detector Parameters

- Vertex Measurement
  - Need to measure decay vertices to <50μm to get proper time distribution.
- Tracking…
  - Would like $\Delta p/p \approx .5\%$ to help distinguish $B \to \pi\pi$ decays from $B \to K\pi$ and $B \to KK$ decays.
  - Provide dE/dx for particle ID.
- EM calorimetry
  - Detect γ's from slow, asymmetric π^0's $\to$ need efficiency down to 20 MeV.
- Hadronic Calorimetry
  - Tag muons.
  - Tag direction of K_L's from decay $B \to \psi K_L$.
- Particle ID
  - Tag strangeness to distinguish B decays from Bbar decays (low p).
  - Tag π's to distinguish $B \to \pi\pi$ decays from $B \to K\pi$ and $B \to KK$ decays (high p).

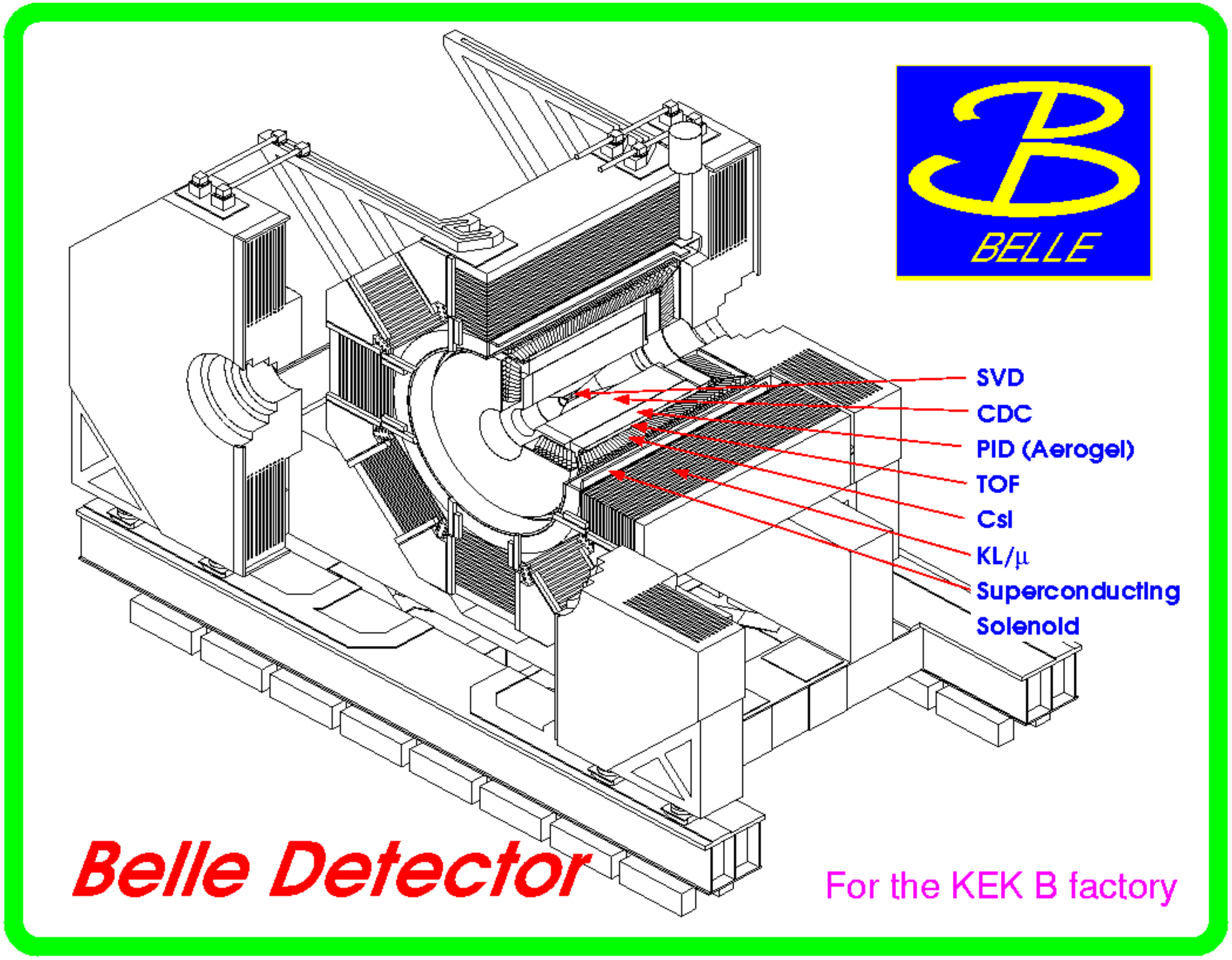
Rely on mature, robust technologies whenever possible!!!

Particle ID needs



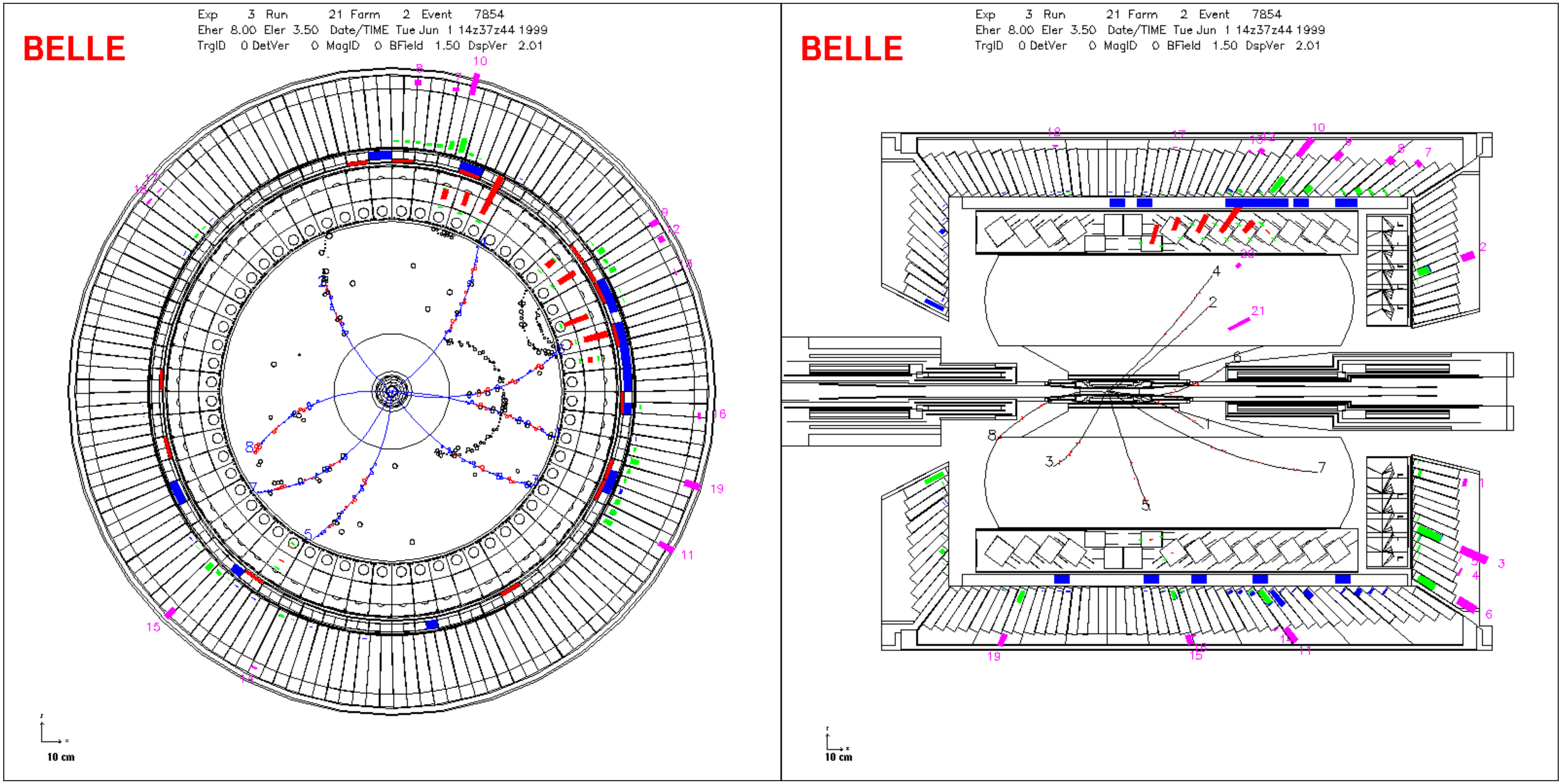
Technology	**Pros**	**Cons**	**Comment**
TOF	Simple.	Only for low momentum.	Included in Belle
dE/dx	Proven. Comes for free.	Only for low momentum	Included in Belle.
TMAE based RICH	Proven in SLD and DELPHI	Universally despised.	Rejected.
CSI RICH	Once seemed promising.	No one could build a working prototype.	Rejected.
DIRC	Rugged. Excellent separation.	New. Contstrants on detector geometry	Babar choice
Aerogel threshold Cerenkov	Simple.	Barely adequate	Belle choice

The Detector

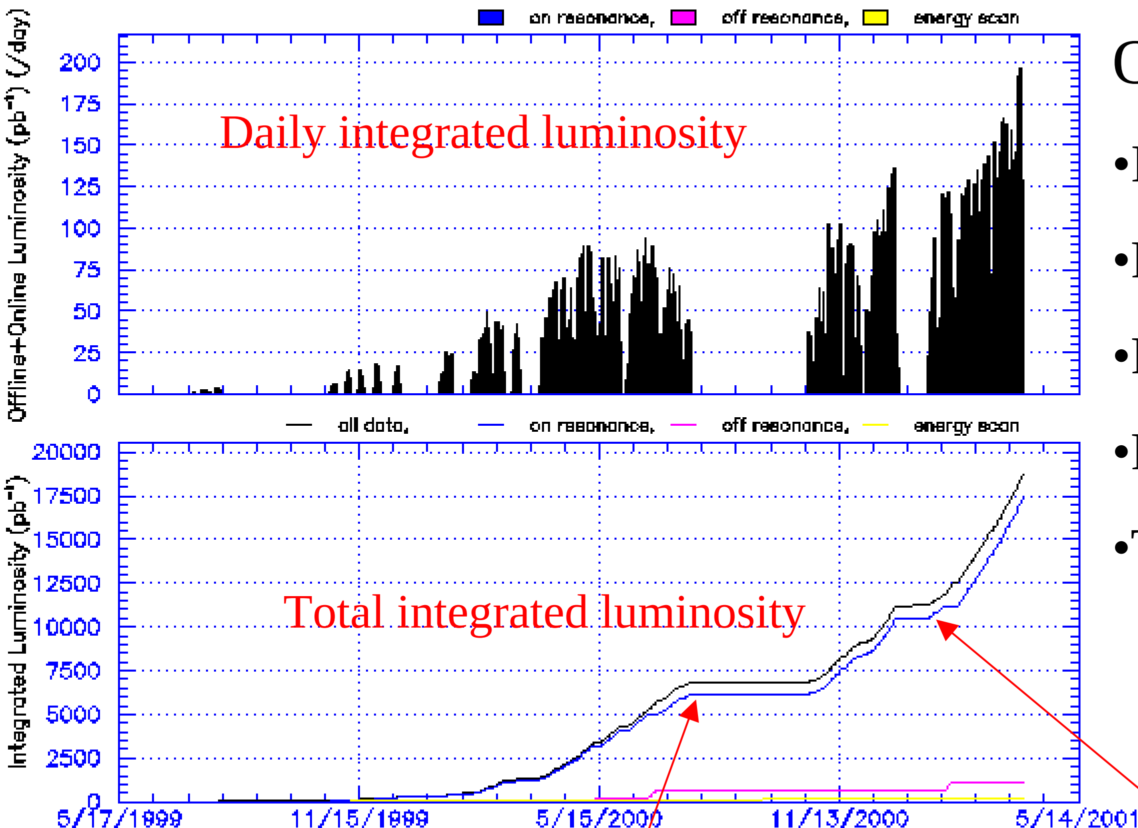


All Finished!!

June 1, 1999: Our First Hadronic Event!!



Luminosity



Our Records:

- •Instantaneous: 3.24×10^{33} cm^{-2}s^{-1}
- •Per (0-24h) day: 194.9 pb^{-1}
- •Per (24 hr) day: 198. pb^{-1}
- •Per week: 1124. pb^{-1}
- •To date: $\approx$17.5 fb^{-1} (on peak)

Note: integrated numbers are accumulated!

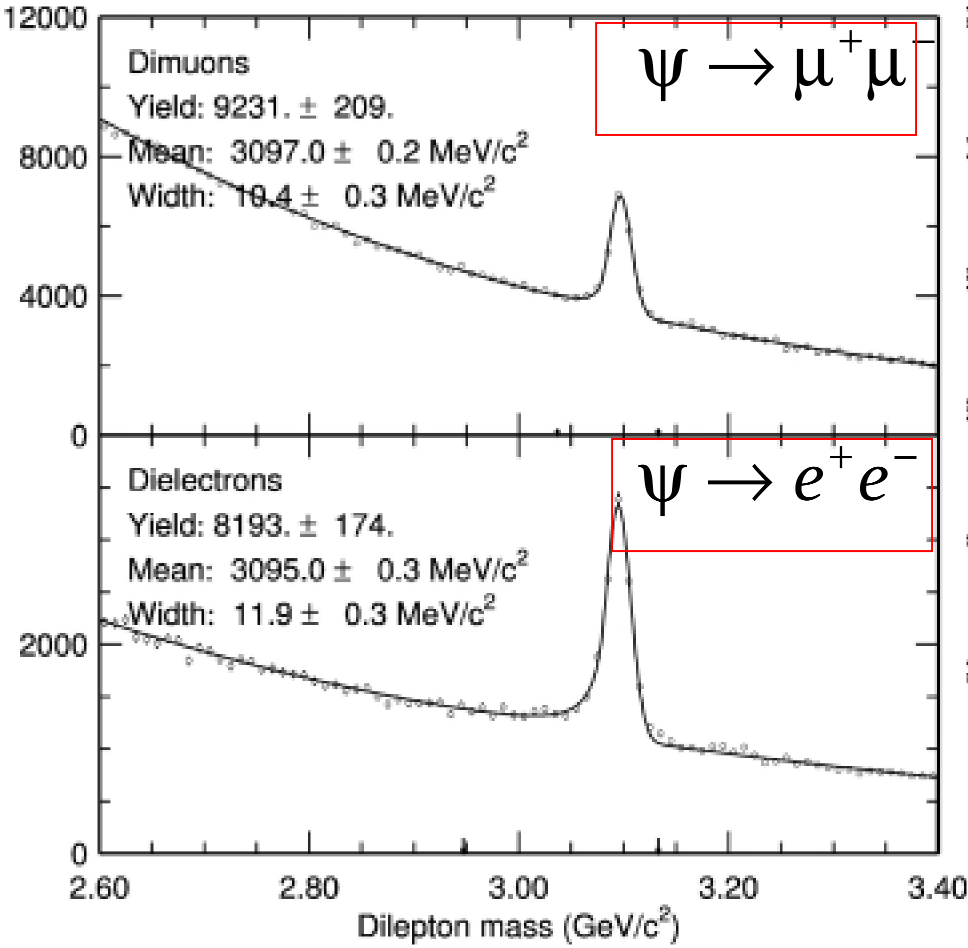
Total for first CP Results (Osaka): 6.2 fb^{-1}

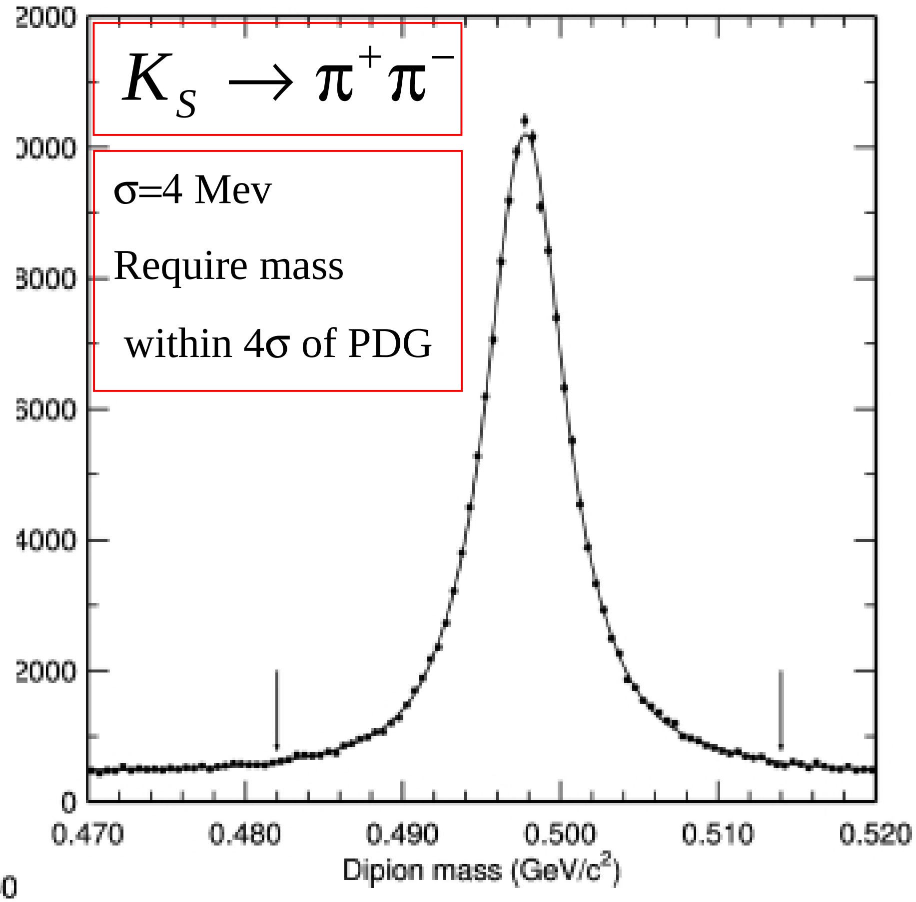
Total for *these* Results: 10.5 fb^{-1}

The Pieces of the Analysis

- Event reconstruction and selection
- Flavor Tagging
- Vertex reconstruction
- CP fitting

J/ψ and K_S Reconstruction





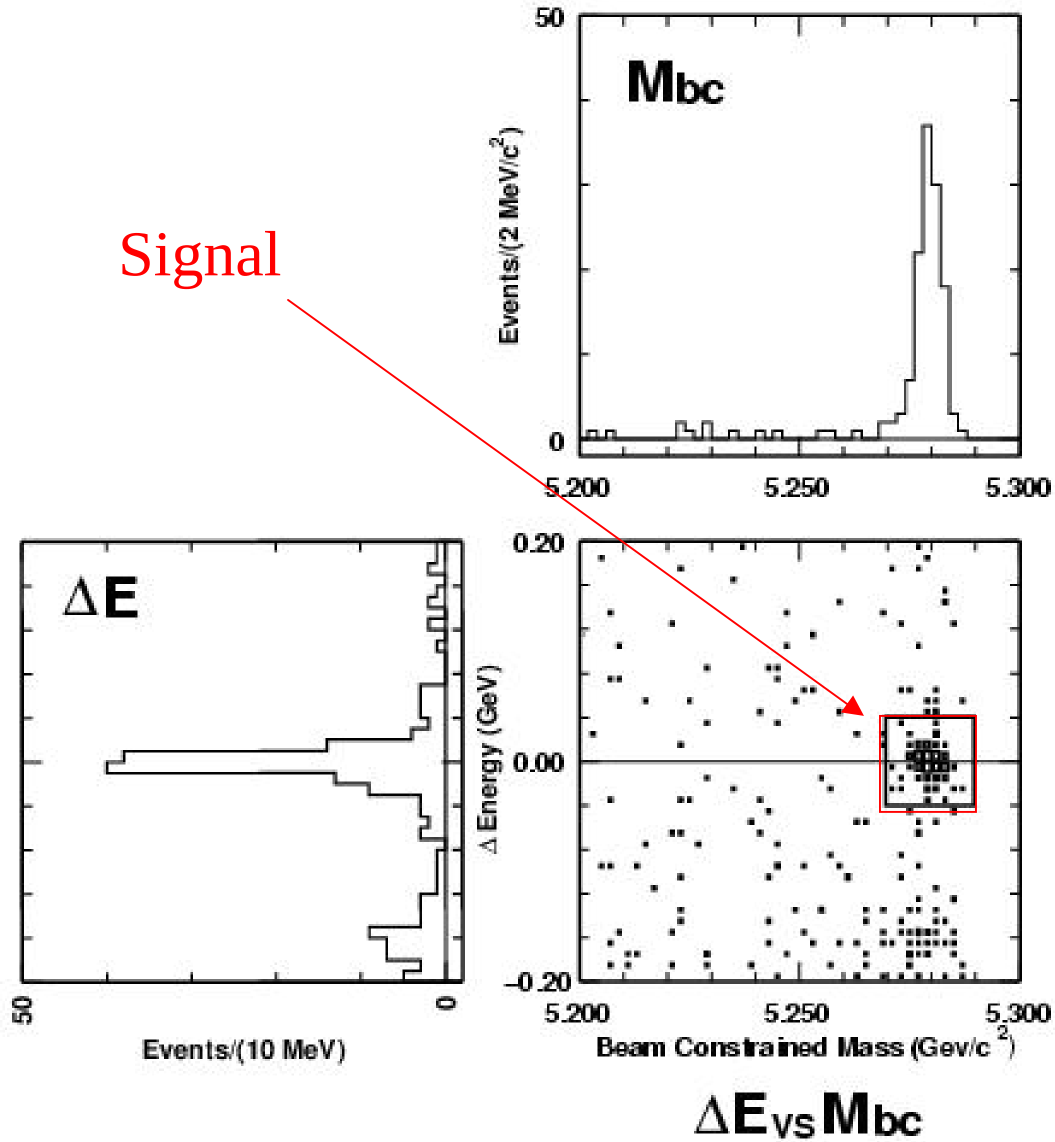
$B \to \psi K_S$ Reconstruction

- In the CM, both *energy* and *momentum* of a real B^0 are constrained.
- Use "Beam-constrained Mass":

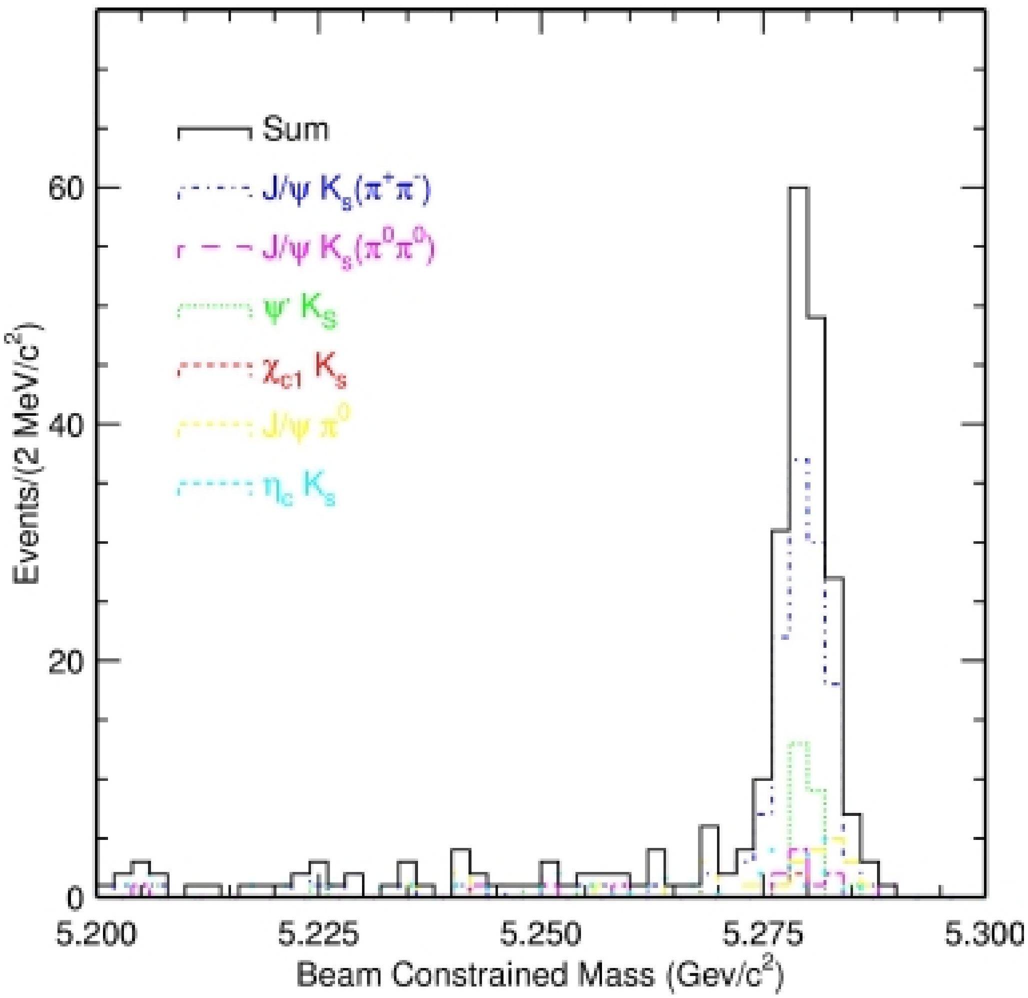
$$M_{BC}^2 = E_{beam}^2 - \left(\sum \vec{p}\right)^2$$

123 Events

3.7 Background

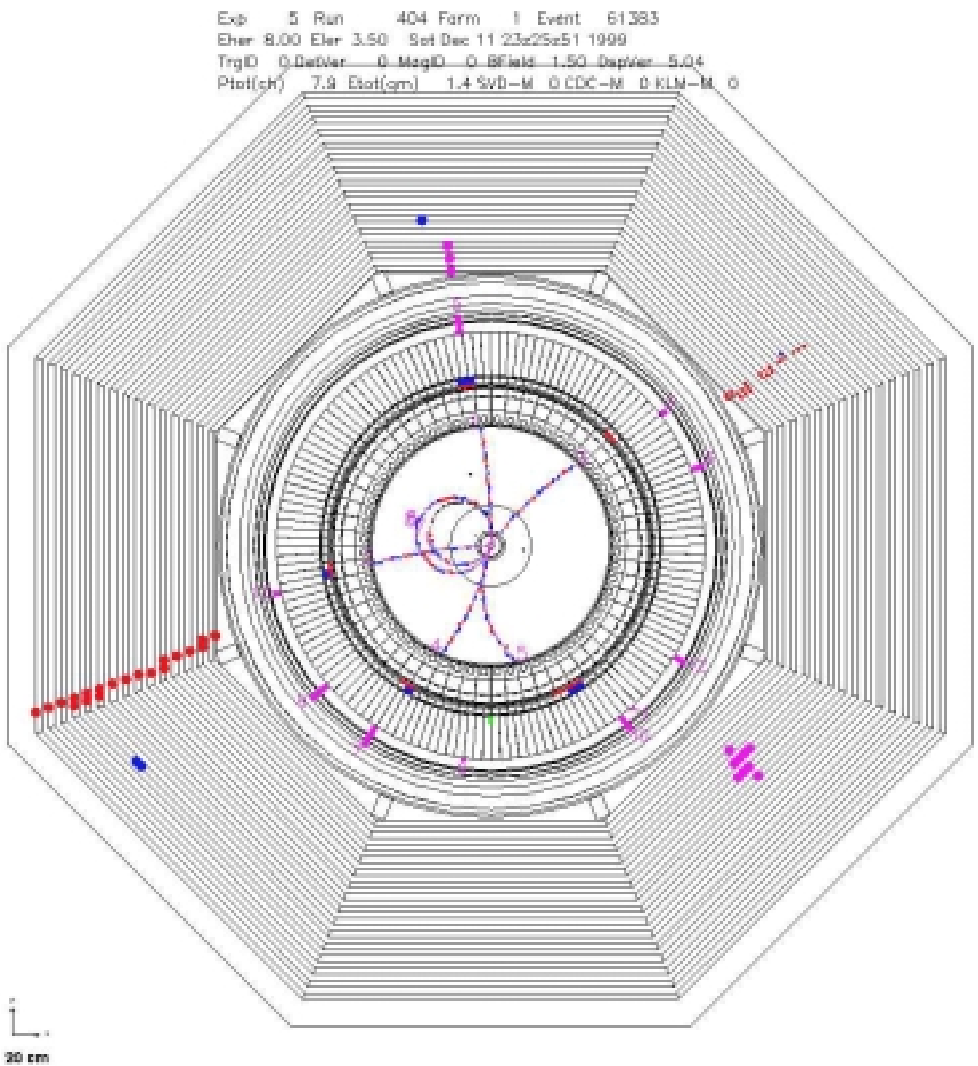


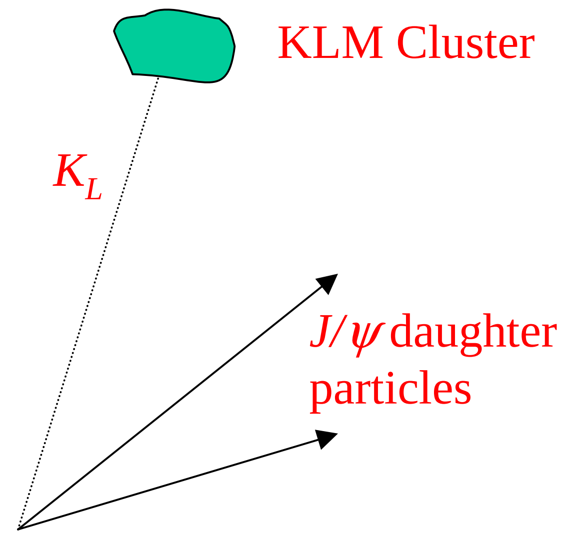
All Fully Reconstructed Modes (i.e. all but ψK_L)



Mode	**Events**	**Background**
$B \to \psi K_S$	123.0	3.7
All Others	71.0	7.3
Total	194.0	10.0

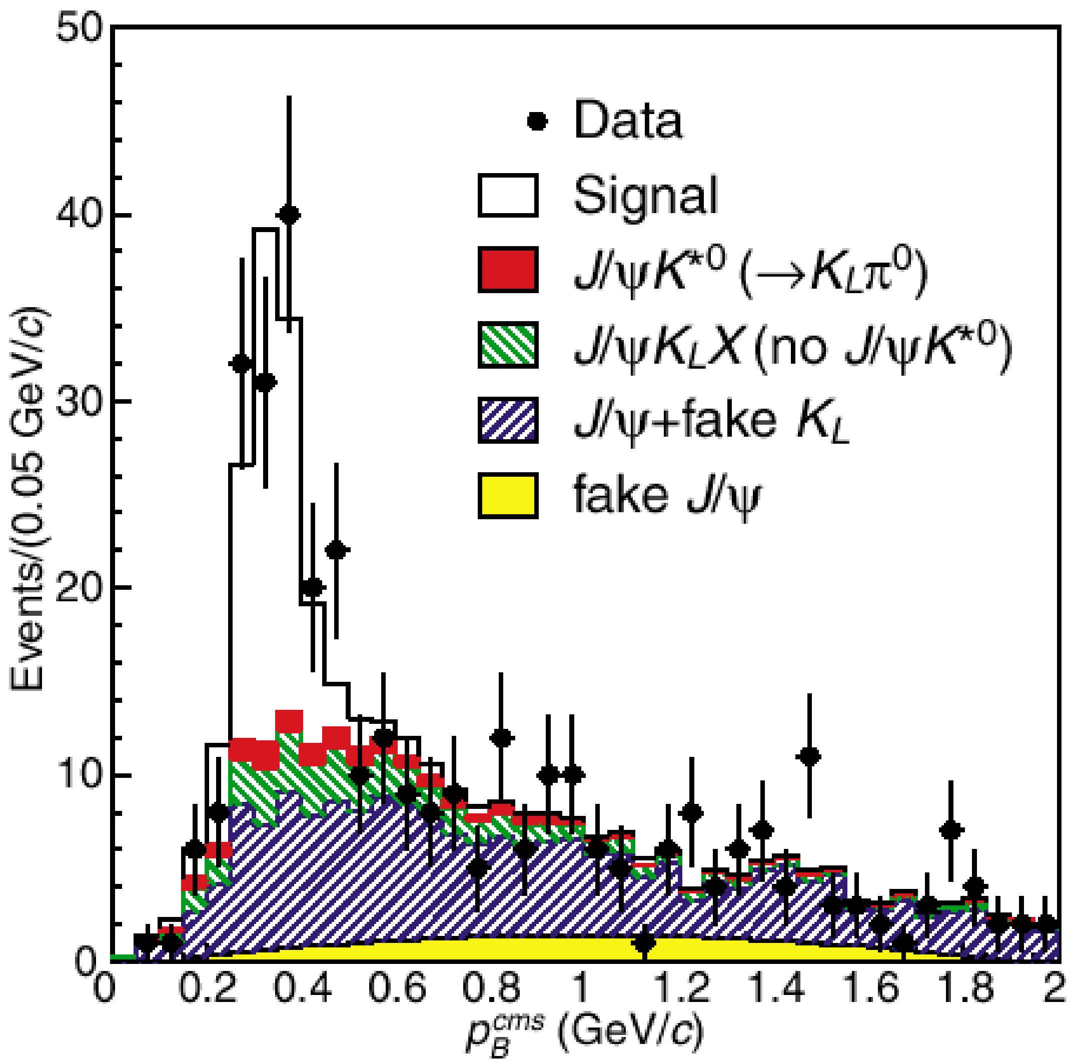
$B \to \psi K_L$ Reconstruction





- Measure direction (only) of K_L in lab frame
- Scale momentum so that $M(K_L + \psi) = M(B^0)$
- Transform to CM frame and look at $p(B^0)$.

$B \to \psi K_L$ Signal



$0 < p_B^* < 2$ GeV/c

Biases spectrum!

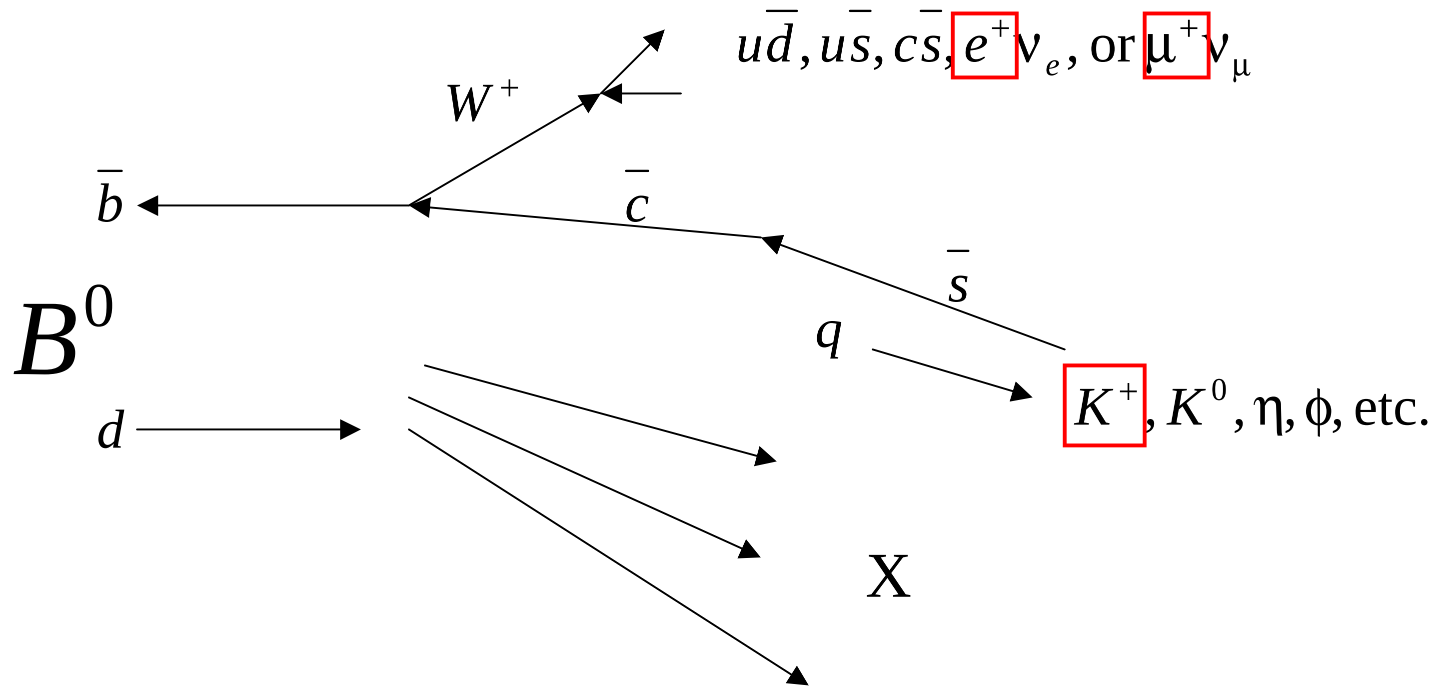
131 Events

54 Background

Complete Charmonium Sample

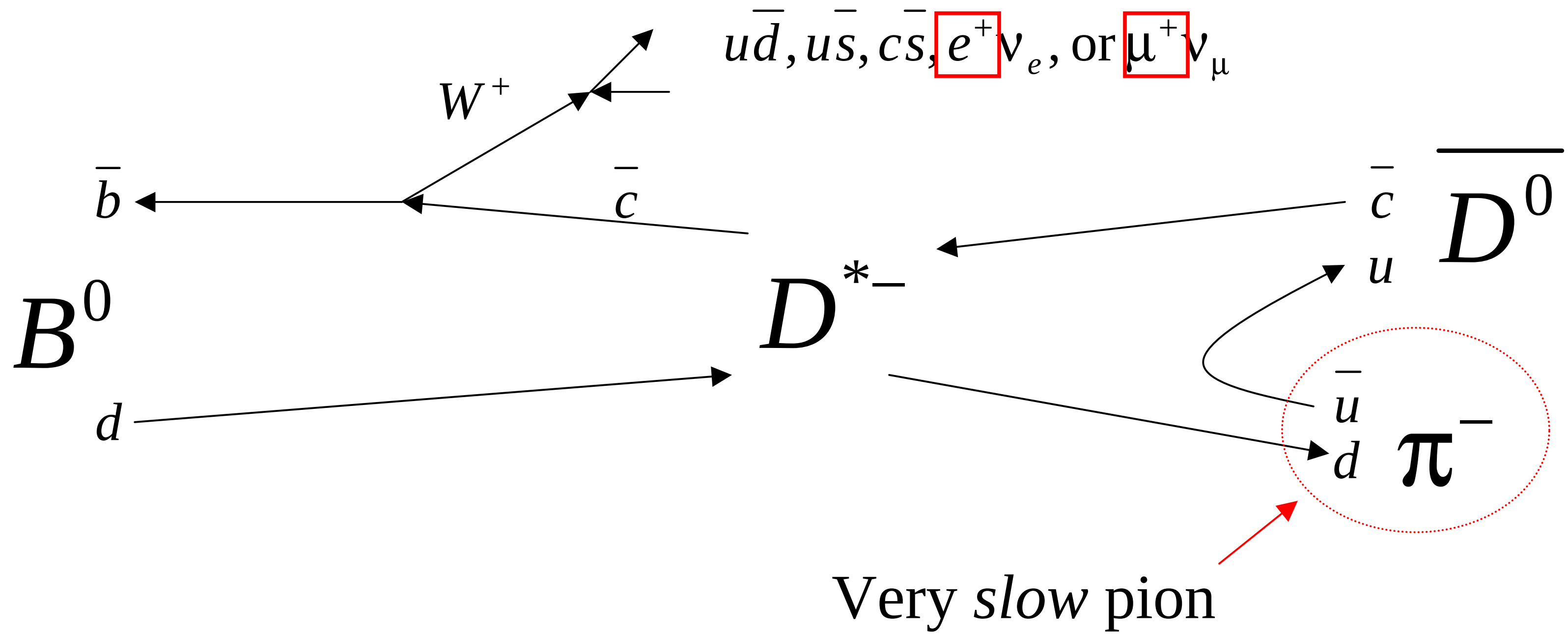
Mode	N_{ev}	N_{bkgd}
$J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$	123	3.7
$J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$	19	2.5
$\psi(2S)(\ell^+\ell^-)K_S(\pi^+\pi^-)$	13	0.3
$\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$	11	0.3
$\chi_{c1}(\gamma J/\psi)K_S(\pi^+\pi^-)$	3	0.5
$\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$	10	2.4
$\eta_c(K_SK^+\pi^-)K_S(\pi^+\pi^-)$	5	0.4
$J/\psi(\ell^+\ell^-)\pi^0$	10	0.9
Sub-total	194	11
$J/\psi(\ell^+\ell^-)K_L$	131	54
Total	325	65

Flavor Tagging



Statistically, B^0's will tend to produce high momentum e^{+}, μ^{+}, and/or K^{+}, while $\overline{B^0}$'s will produce the opposites.

Flavor Tagging (Slow Pion)



B^0's will tend to produce slow π^-.

Event by Event Tagging Quality

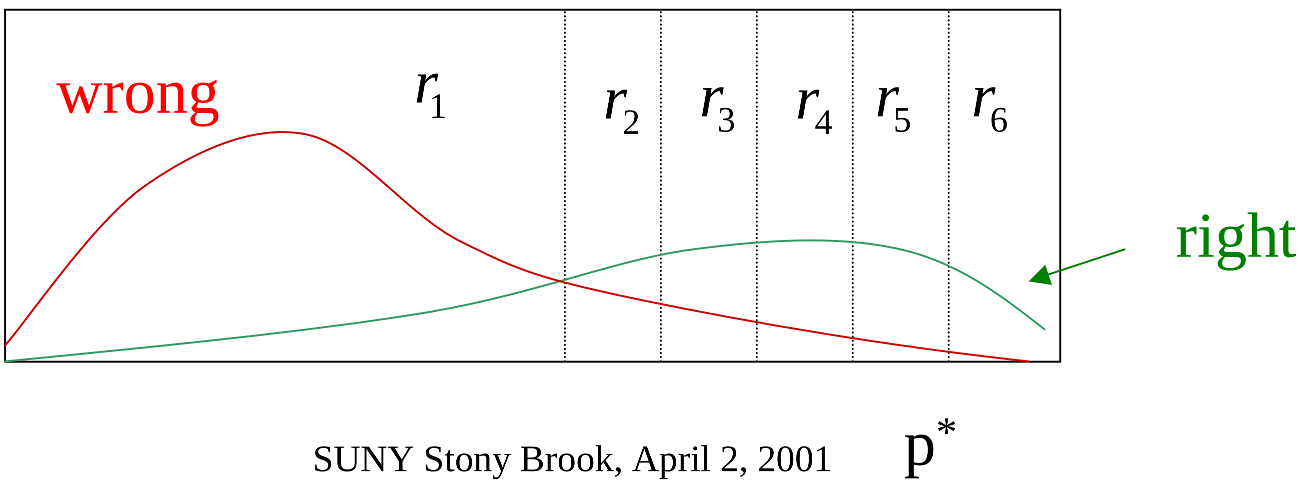
If we tag events wrongly, we'll measure CP violation as

$$p(B^0_{tagged} \to f_{CP}) \propto e^{-\Gamma t}\left[(1-w)(1-\sin 2\phi_1 \sin \Delta m \Delta t) + w(1+\sin 2\phi_1 \sin \Delta m \Delta t)\right]$$
$$= e^{-\Gamma t}\left[\{1-(1-2w)\sin 2\phi_1 \sin \Delta m \Delta t\}\right]$$

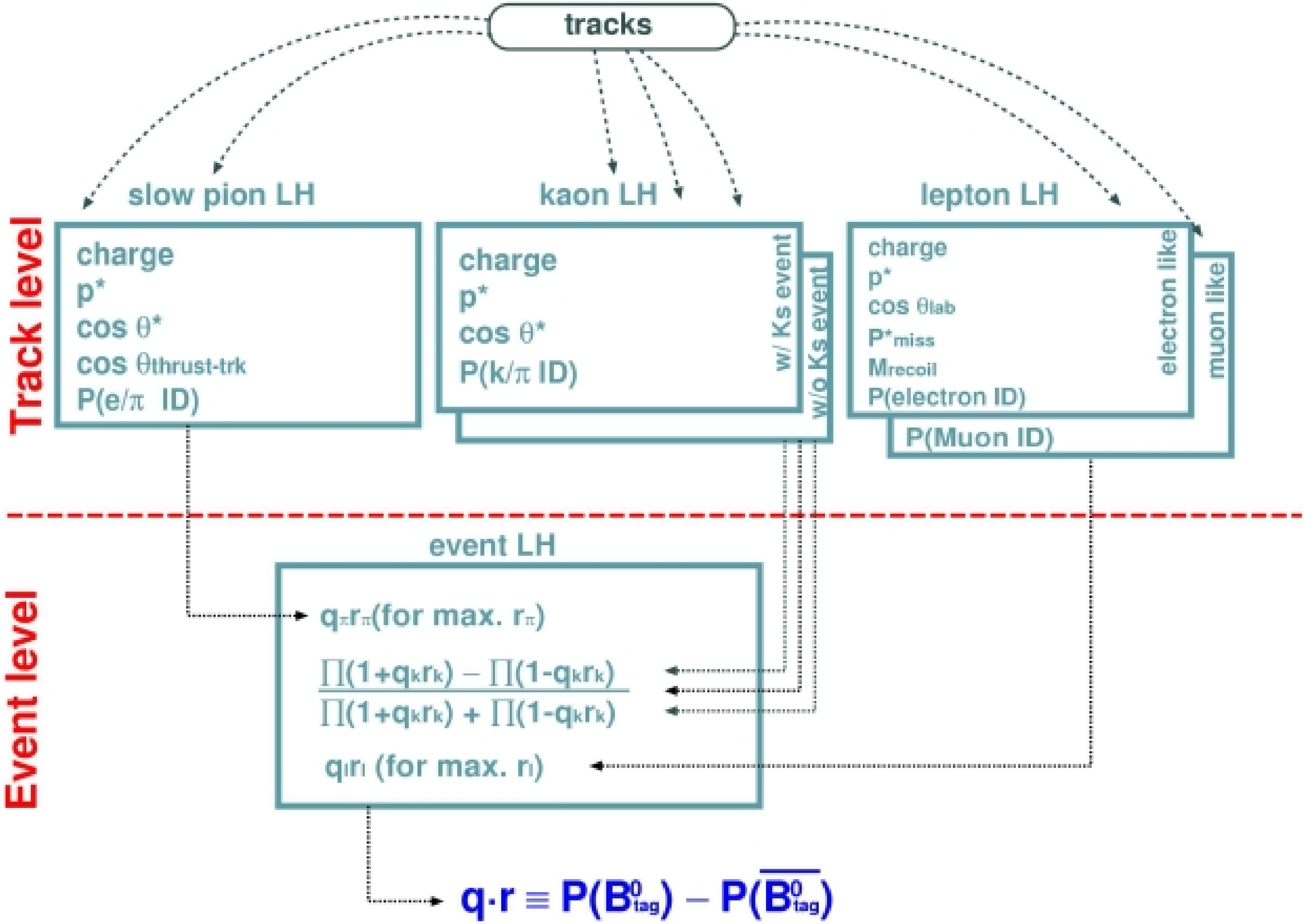
So the measurement is *diluted* by a factor $(1-2w) \equiv r$

Ideally, we can determine this on an event by event basis to be used in the CP fit

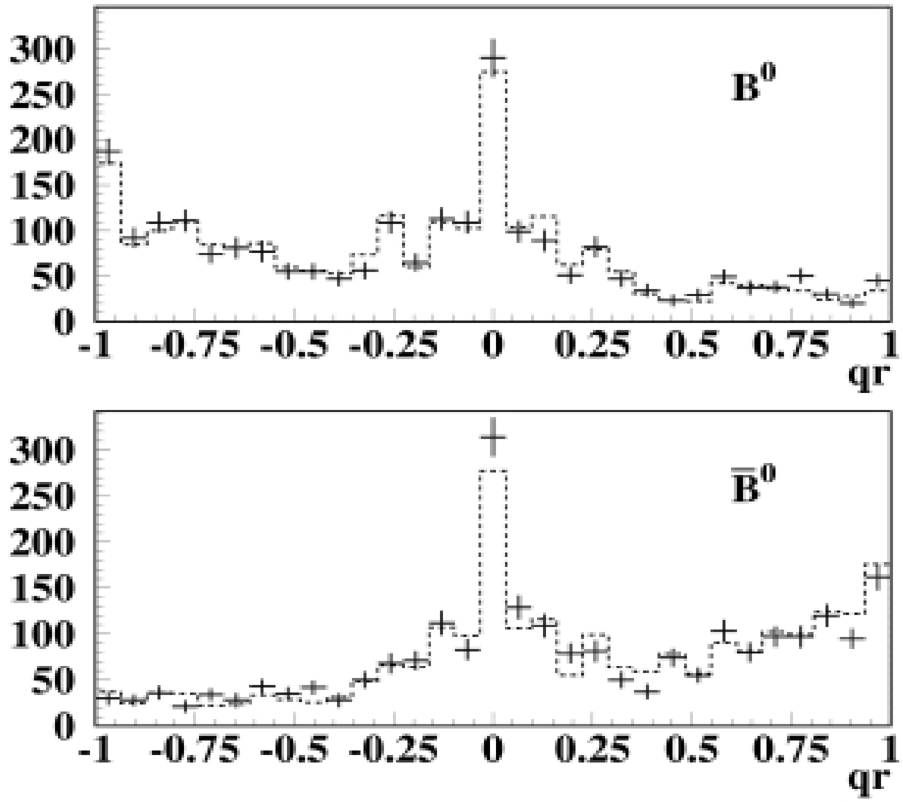
Example, for high-*p* lepton



Multi-dimensional Flavor Tagging



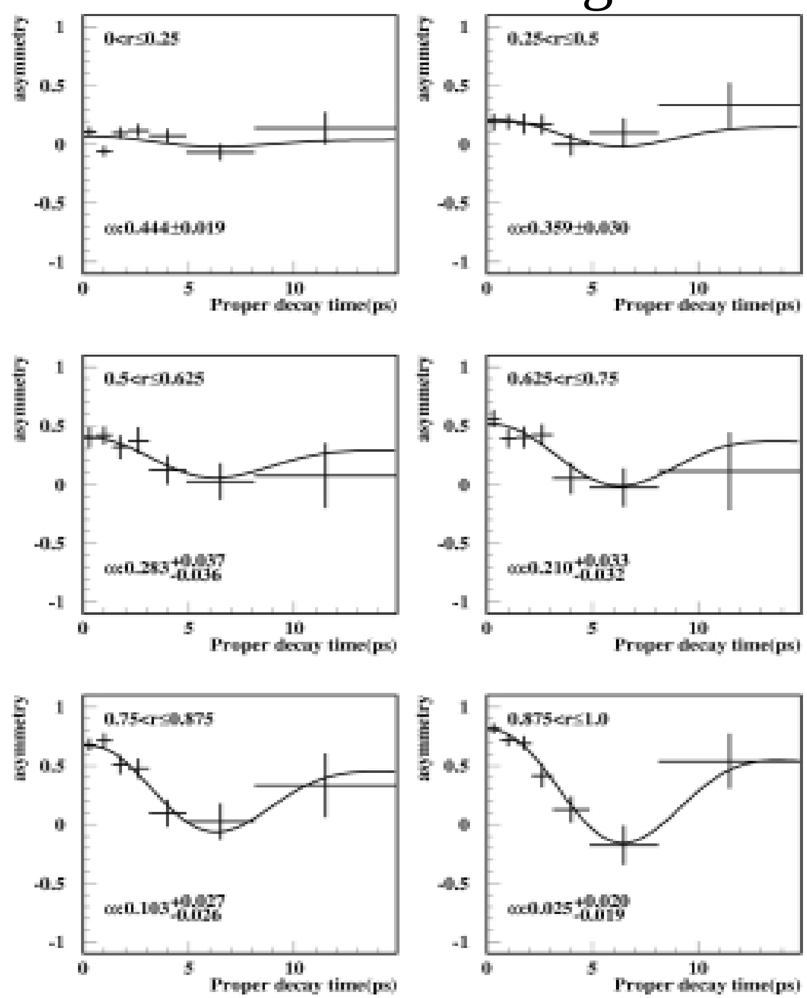
Comparison Between MC and Data



$D^* l\nu$ Events + Data

--- MC

Diluted B-Mixing



Tagging Efficiency

TABLE I. Experimentally determined event fractions (f_l) and incorrect flavor assignment probabilities (w_l) for each r interval.

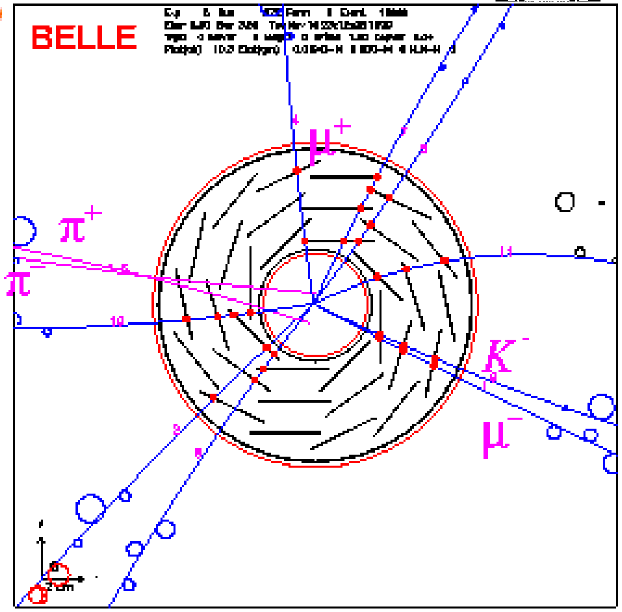
l	r	f_l	w_l
1	$0.000 - 0.250$	0.393 ± 0.014	$0.470^{+0.031}_{-0.035}$
2	$0.250 - 0.500$	0.154 ± 0.007	$0.336^{+0.039}_{-0.042}$
3	$0.500 - 0.625$	0.092 ± 0.005	$0.286^{+0.037}_{-0.035}$
4	$0.625 - 0.750$	0.100 ± 0.005	$0.210^{+0.033}_{-0.031}$
5	$0.750 - 0.875$	0.121 ± 0.006	$0.098^{+0.028}_{-0.026}$
6	$0.875 - 1.000$	0.134 ± 0.006	$0.020^{+0.023}_{-0.019}$

Experimentally determined w values in each *r* region

Tagging efficiency ε_T = 99.4% (vs. 99.3% in MC)

Effective efficiency $\varepsilon_{eff} = \varepsilon_T(1\text{-}2w)^2$ = **27.0%** (vs. 27.4% in MC)

Vertex Reconstruction



- Common requirements in vertexing
  - # of associated SVD hits > 2 for each track
  - IP constraint in vertex reconstruction
- *CP* side vertex reconstruction
  - Event is rejected if reduced $\chi^2 > 100$.
- Tag side vertex reconstruction
  - Track parameters measured from *CP* vertex must satisfy:
    - $|\Delta z|<1.8$mm, $|\sigma z|<500\mu$m, $|\Delta r|<500\mu$m
  - Iteration until reduced $\chi^2 < 20$ while discarding worst track.
- $|z_{CP} - z_{\rm tag}|<2$mm $(\approx 10\,\tau_B)$

Overall efficiency = ~87%.   In total 282 events for the CP fit.

CP Fit (Probability Density Function)

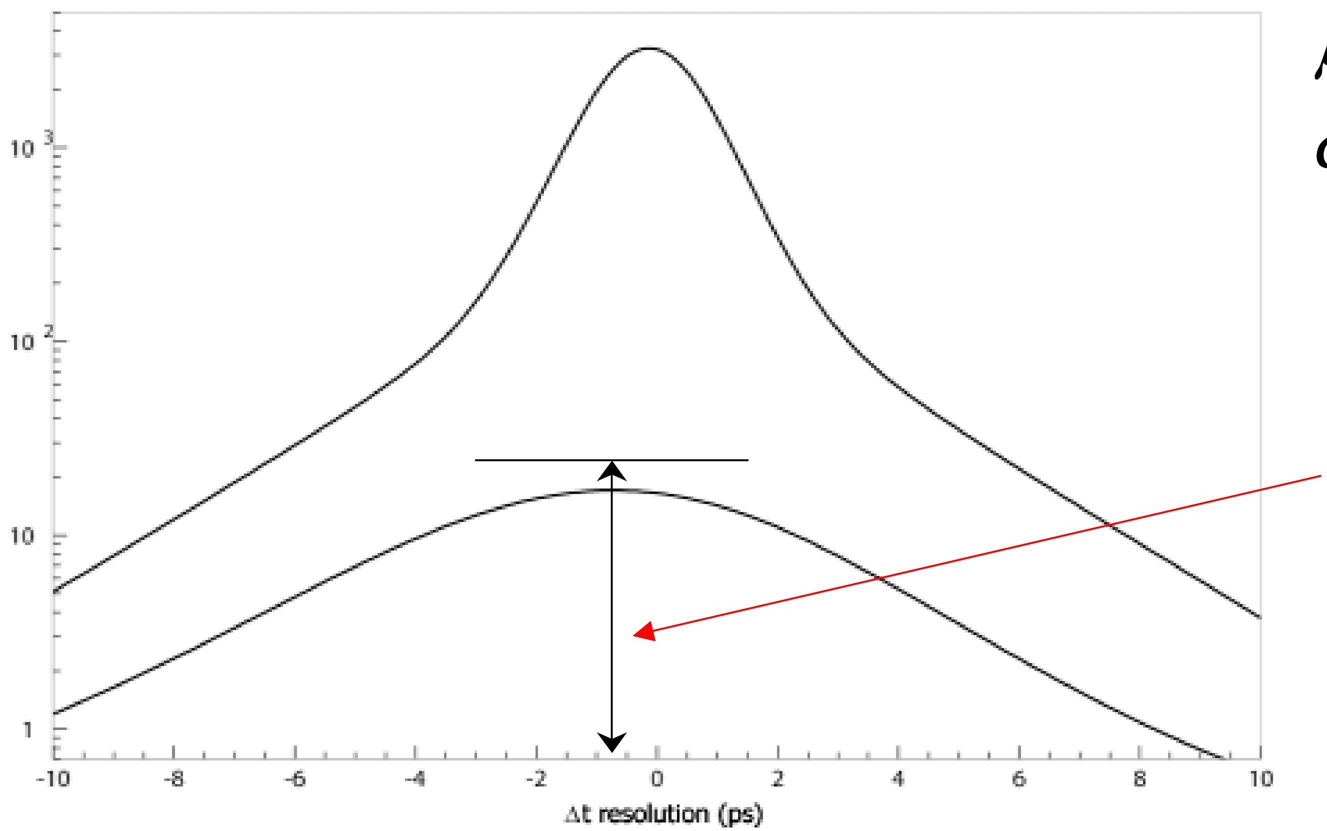
$$f(\Delta t;\sin 2\phi_1) = e^{-\frac{|\Delta t|}{\tau_B}}\left(1 \pm \sin 2\phi_1 \sin x_d \frac{\Delta t}{\tau_B}\right)$$

$$PDF = \int (1 - f_{BG})\, f(t') R(t' - \Delta t)\, dt' + f_{BG} PDF_{BG}(\Delta t)$$

- f_{BG} = background fraction. Determined from a 2D fit of *E* vs *M*.
- $R(\Delta t)$ = resolution function. Determined from D^*'s and MC.
- $PDF_{BG}(\Delta t)$ = probability density function of background. Determined from ψK sideband (210 events).

Resolution Function

Fit with a double-Gaussian…



μ_{main} -0.09 ps

σ_{main} 1.54 ps

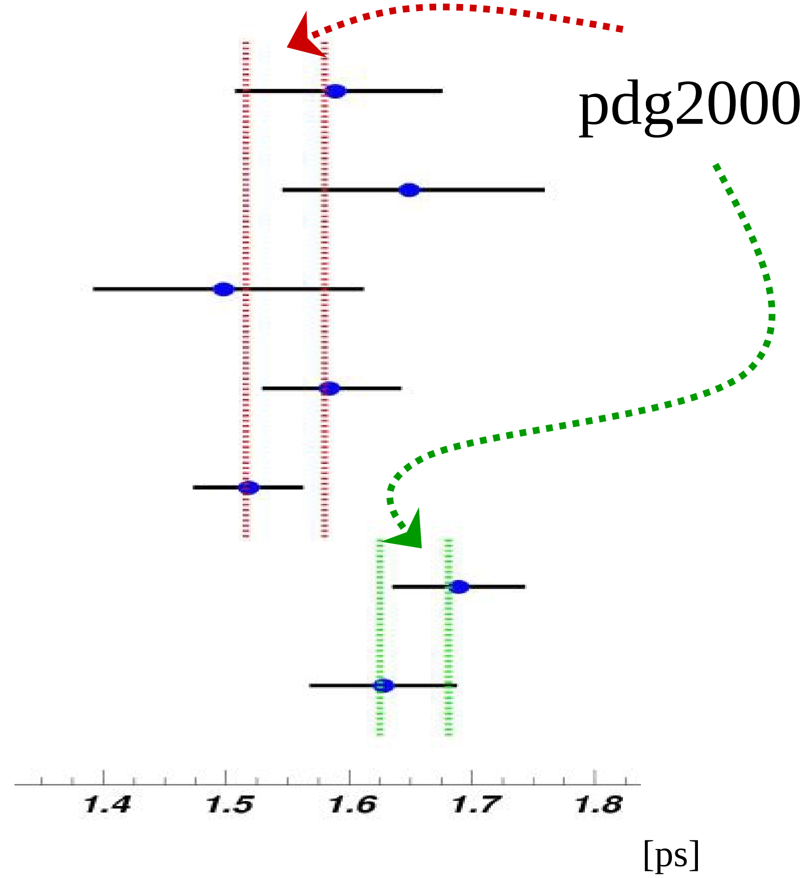
μ_{tail} -0.78 ps

σ_{tail} 3.78 ps

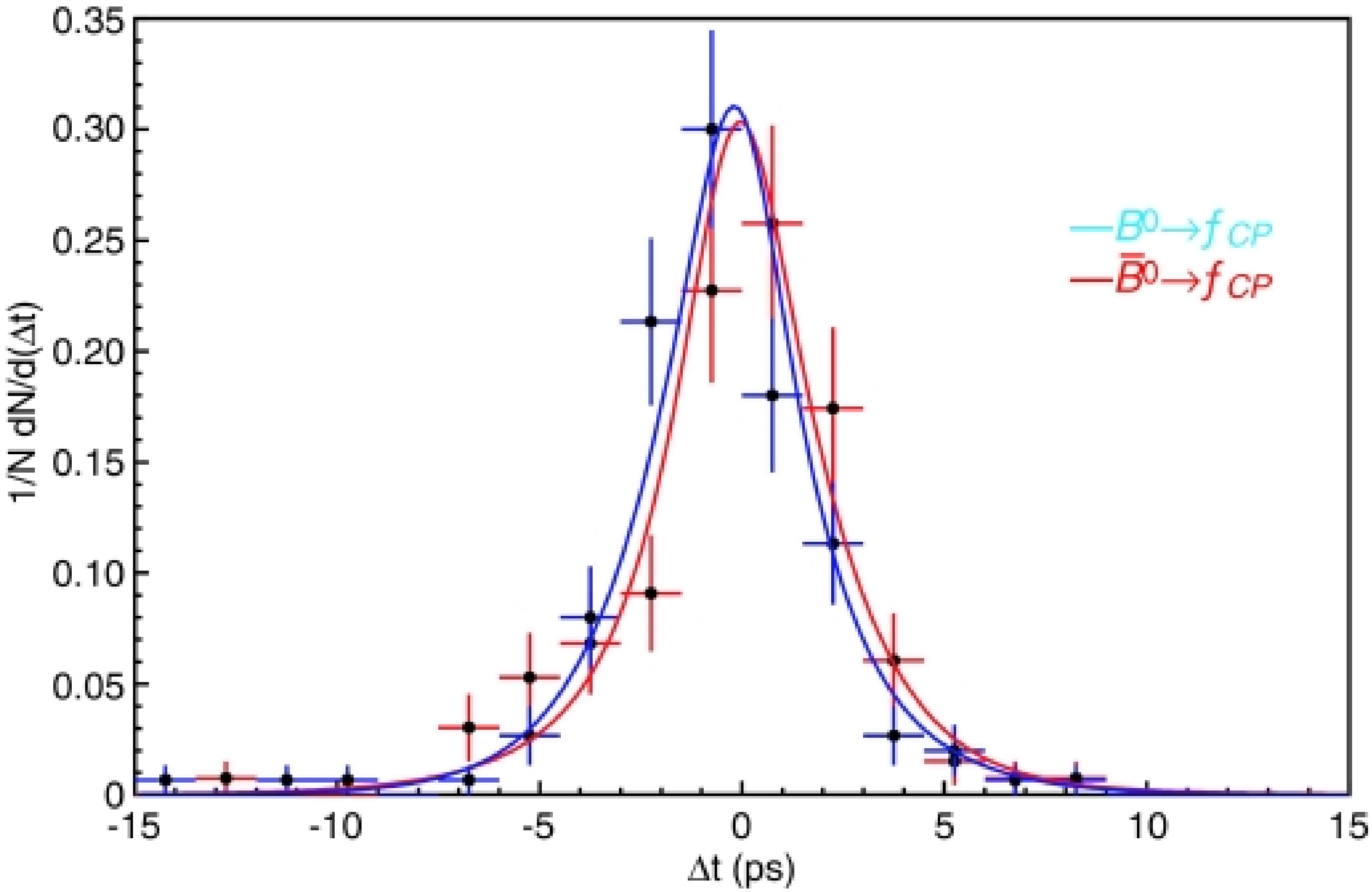
f_{tail} 0.018

Test of Vertexing – B Lifetime

Mode	**Lifetime (ps)**
$B^0 \rightarrow D^+\pi^-$	$1.59^{+.09}_{-.08}$
$D^{*+}\pi^-$	$1.65^{+.11}_{-.10}$
$D^{*+}\rho^-$	1.50 ± 0.11
Combined	1.59 ± 0.05
$D^{*+}l^-\nu$	1.52 ± 0.05
$B^- \rightarrow D^0\pi^-$	1.68 ± 0.05
$D^{*0}l^-\nu$	1.63 ± 0.06



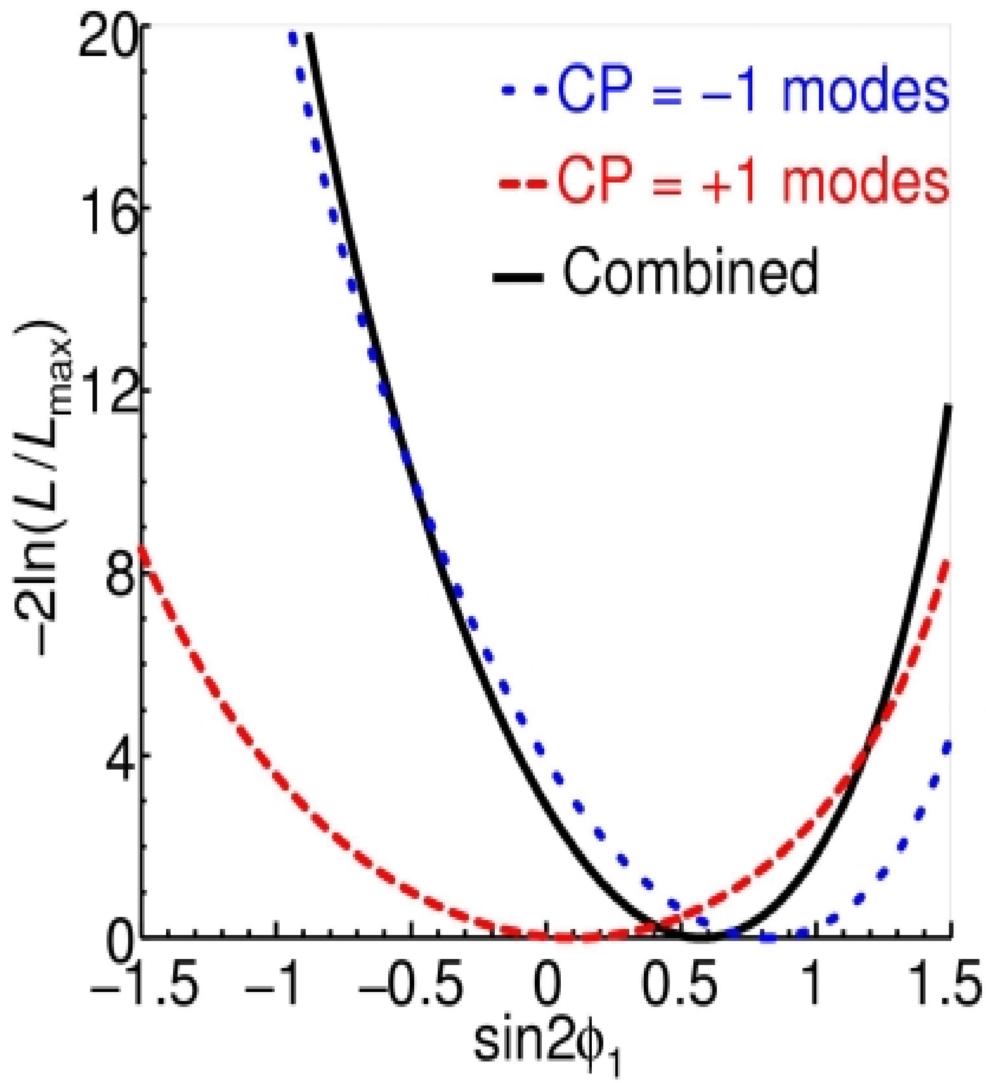
The Combined Fit (All Charmonium States)



$$\sin 2\phi_1 = .58^{+.32}_{-.34}(stat)$$

Individual Subsamples

Mode	Fit (stat. err.)
Non-CP	0.065 ± 0.075
$B \to \psi K_S$	$1.21^{+.40}_{-.47}$
$B \to \psi K_L$	-0.04 ± 0.60
CP = -1	$0.82^{+.36}_{-.41}$
CP = +1	$0.10^{+.57}_{-.60}$
All CP	$0.58^{+.32}_{-.34}$



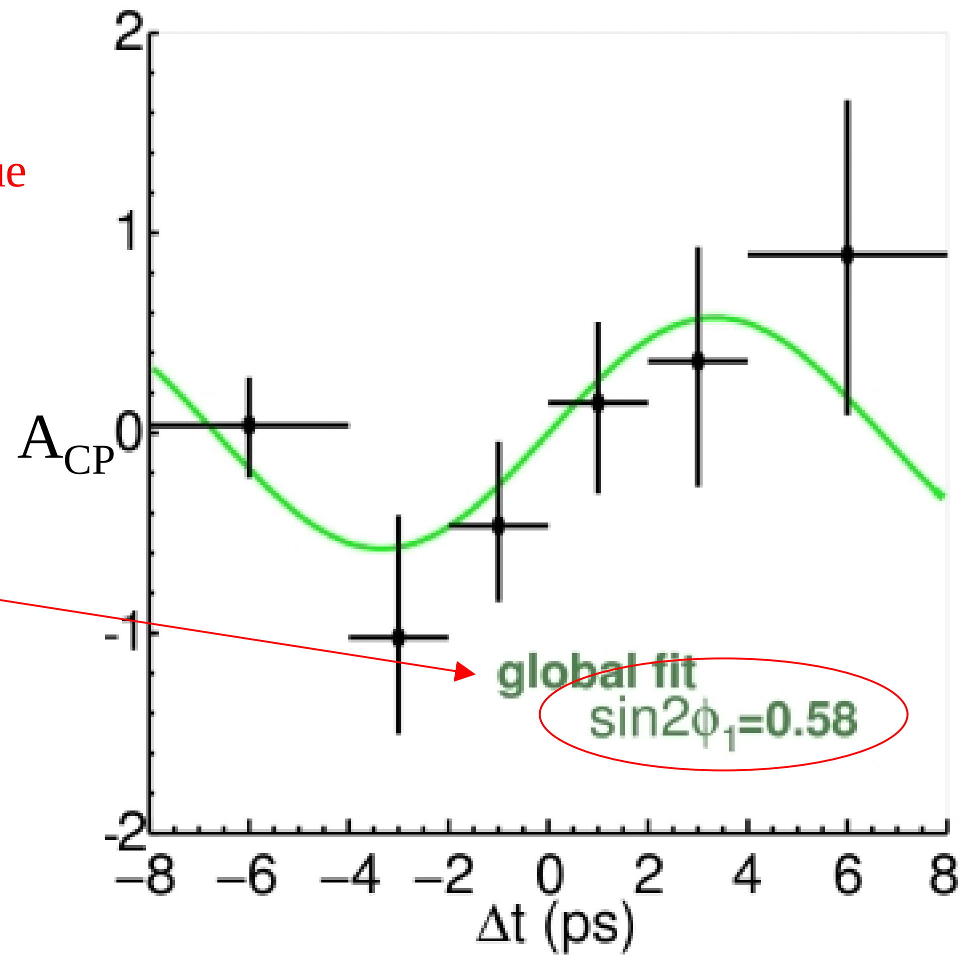
Consistency Check

Plot asymmetry in individual time bins…

Fix at PDG value

$$\sin 2\phi_1 \sin \Delta m \Delta t$$

Our fit



Sources of Systematic Error

Source	σ_+	σ_-
Wrong tag fraction	+.05	-.07
Resolution for signal	+.01	-.01
Background Shape	+.01	-.01
Physics Parameters	+.03	-.04
IP Profile	+.02	-.01
Background (not K_L)	+.03	-.02
Background (K_L)	+.05	-.05
Total	**+.09**	**-.10**

- Bottom Line

$$\sin 2\phi_1 = .58^{+.32}_{-.34}(stat)^{+.09}_{-.10}(syst.)$$

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Other Recent Publications

- "Measurement of B^0_d - B^0_d-bar Mixing Rate from the Time Evolution of Dilepton Events at Upsilon(4S)" (*to appear in PRL)*
- "A Measurement of the Branching Fraction for the Inclusive B->Xs gamma Decays with Belle" (*submitted to PLB)*
- "Measurement of Inclusive Production of Neutral Pions from Upsilon(4S) Decays" (*submitted to PRL)*

+ Several More in the Pipeline!!

Summary and Outlook

- Belle is working very well!!
- Our current value of *sin2ϕ_1*, based on 10.5 fb^{-1} of data is

$$\sin 2\phi_1 = .58^{+.32}_{-.34}(stat)^{+.09}_{-.10}(syst.)$$

- This is consistent with the BaBar value of

  $$\sin 2\beta = .34 \pm .20(stat) \pm .05(syst.)$$

  and with other previous results (CDF, LEP)

- The probability of observing this value if CP is conserved is 4.9%
- The next few years should be very exciting!