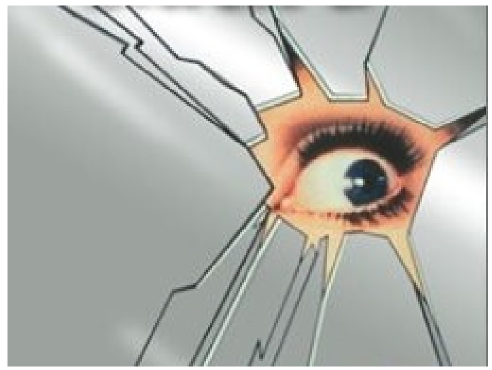
The Mirror Crack'd*: History and Status of CP Violation Studies



Eric Prebys (UR '90), Fermi National Accelerator Laboratory*

Representing the

BELLE Collaboration

*apologies to Agatha Christie

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.
Toyama N.C. of Martime technology	University of Tsukuba
Utkal University	Virginia Polytechnic Institute
Yonsei University	

Just to set the tone….

Dear Eric,

I just returned to Rochester and I am happy to know that Tom has invited you for a colloquium on Sep 26. Can you send me a title of your talk at the earliest. I would like to tell you a few things that Tom may not have mentioned. First, you will be the first speaker of the semester and, therefore, you carry a great responsibility for presenting a very good colloquium. Second, since our colloquium attendance has thinned over the years (because of bad talks, specialized talks), I have assured the students that I will only invite extraordinary speakers who can give a very general talk to graduate students across all disciplines. So, I would like you to prepare your talk keeping this in mind. In particular, what this means is that please do not make it a talk on experimental physics, rather on physics. Remember the time when you were a student and the kinds of things you hated in colloquia, please avoid them. Not all the students will be from high energy physics. In fact, many are from optics, astronomy and so a talk with less display of detectors etc and with a greater balance of theoretical motivation and the explanation of results would be highly appreciated.

Why am I telling you all this? Well, first of all, you were our former student and as such *I have a right to ask you for things*. Second, you will be the first speaker and if the students are not thrilled with your talk, the attendance may shrink in the subsequent talks. On the other hand, if your talk is superb, which I hope it will be, more people will show up for the later talks (people have a tendency to extrapolate). In any case, please keep in mind that you will be talking to a general audience and not to a group of experimentalists.

Let me know when your itinerary is complete, but please send me a title in a couple of days.

With very best regards,

Ashok.

Outline

- Why do we care?
- History
  - Parity Violation
  - V-A Currents and CP (almost) Conservation
  - CP Violation in the Neutral K System
  - The Cabbibo-Kobayashi-Maskowa Mechanism
  - “The” Unitarity Triangle
- The Present
  - Direct CP Violation in the Neutral K System (ε’/ε)
  - Indirect CP Violation in the B meson System (B-Factories)
- The Future?

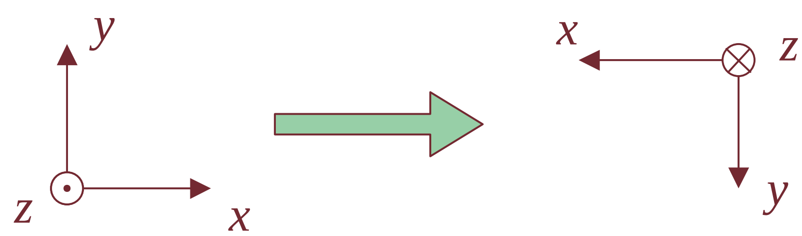
Why do We Care?

- Dirac first predicted antimatter in 1930 as a consequence of the "extra" solutions to his relativistic formulation of quantum mechanics - and was widely ridiculed.
- The positron (anti-electron) was discovered by Anderson in 1932 and the anti-proton was discovered by Segre and Chamberlain in 1955.
- Now we are all quite comfortable with the idea of antimatter as "equal and opposite" to matter, e.g.

> "Of course, there is only one correct mixing ratio of matter and antimatter: **one to one**!" – Star Trek, The Next Generation

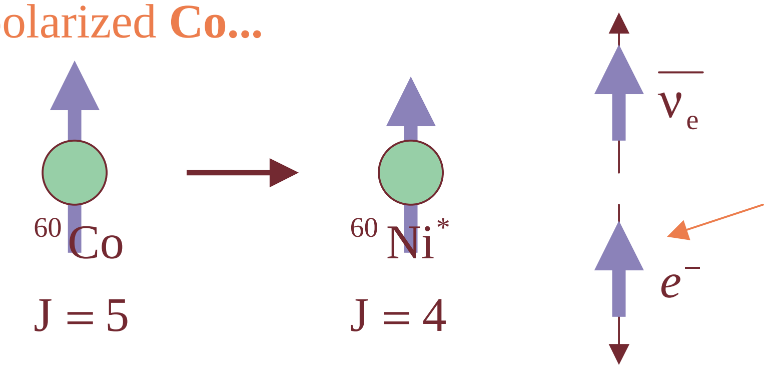
- …but why does the universe seem to be made entirely of matter?
- Why do there seem to be *tiny* differences in the physics of matter and antimatter?
- These legitimately qualify as **"big questions".**

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…

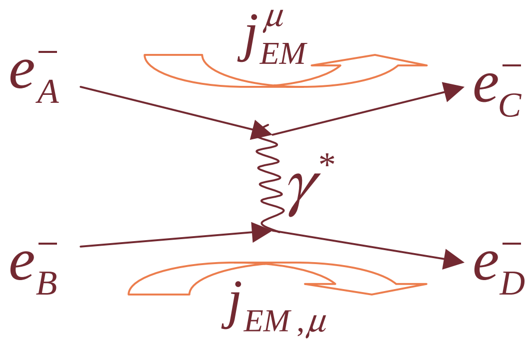
Example: β decay of polarized **Co...**



electron preferentially emitted opposite spin direction

Weak Currents and Parity Violation

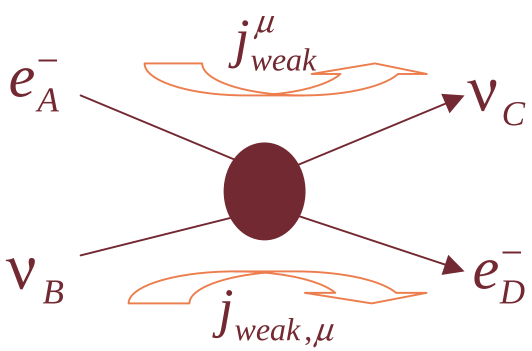
Review: QED



$$A \propto j^{\mu}_{CA}\, j_{DB,\mu} = \left(\overline{u_C}\gamma^{\mu}u_A\right)\left(\overline{u_D}\gamma_{\mu}u_B\right)$$

Transform like vectors

For weak interactions, *try* (“four fermion interaction”)



axial vector

$$j^{\mu} = \overline{u_C}\left(c_v\gamma^{\mu} + c_A\gamma^5\gamma^{\mu}\right)u_A$$

vector

Manifestly Violates Parity!!

“V-A” Current

Experimentally, it was found that data were best described by

$$j^{\mu}_{weak} = \overline{u_C}\left(\gamma^{\mu} - \gamma^5\gamma^{\mu}\right)u_A$$

Maximum Parity Violation!!!!

Recall that for Direct Spinors, the left handed projection operator is

$$u_L = P_L u = \left(\frac{1-\gamma^5}{2}\right)u \Rightarrow j^{\mu}_{weak} \propto \overline{u_L}\gamma^{\mu}u_L$$

“Left-handed” current

For massless particles, spinor state = helicity state

→ Only Left-handed Neutrinos

CP Conservation (sort of)

When we apply the usual Dirac gymnastics, we find that for *anti-particles*

$$j^{\mu}_{weak} = \overline{\nu_C}\left(\gamma^{\mu} + \gamma^5\gamma^{\mu}\right)\nu_A \propto \overline{\nu_R}\gamma^{\mu}\nu_R$$

Right-handed current

➡ Only Right-handed anti-Neutrinos

⇨ Overall symmetry restored under the combined operations of C(harge conjugation) and P(arity).

⇨ CP Conservation!!!

well, maybe not….

The Neutral Kaon System

In experiments in the 1950s, it was found that there were two types of neutral strange particles, of indistinguishable mass (498 MeV), but with different decay properties.

$$K_{L(ong)} \Rightarrow 3\pi$$ CP = -1

$$K_{S(hort)} \Rightarrow 2\pi$$ CP = +1

Because $3*m_\pi \approx m_K$, the K_L lives about 600 times longer than the K_S, hence the names.

Strangeness eigenstates

Possible explanation:

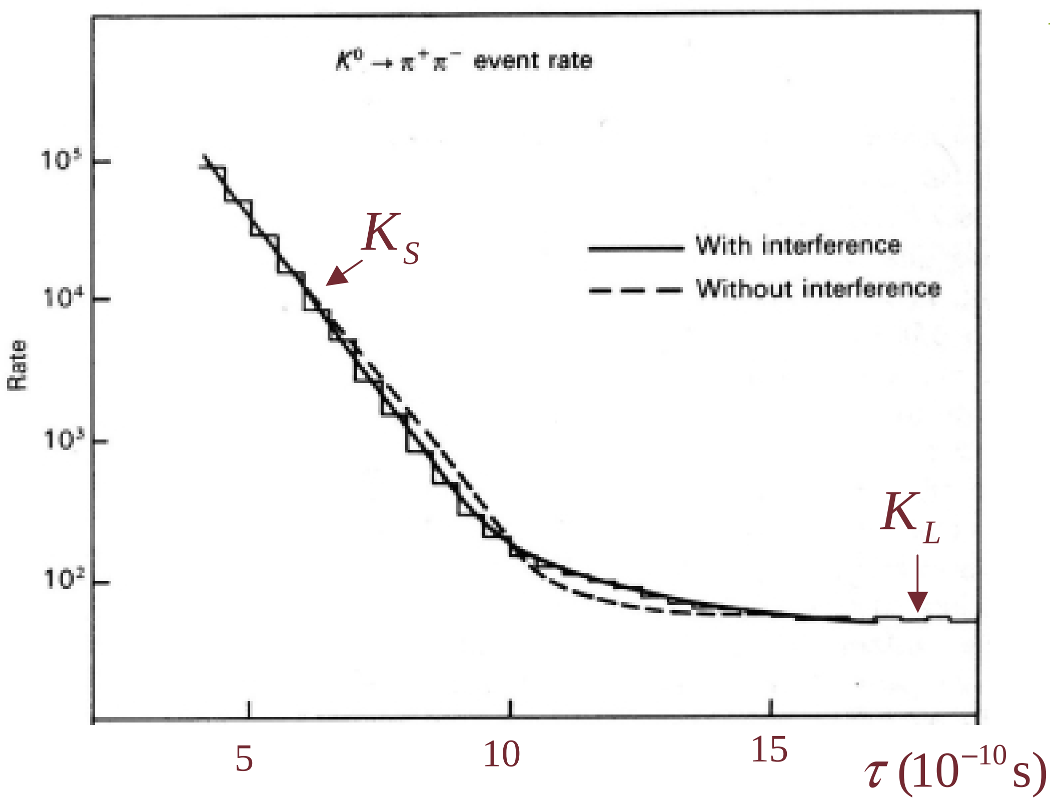
$$\left|K_S\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K_0\right\rangle + \left|\overline{K_0}\right\rangle\right)$$

$$\left|K_L\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K_0\right\rangle - \left|\overline{K_0}\right\rangle\right)$$

close, but not *quite* correct…

CP Violation in the Neutral K System

In 1964, Fitch, Cronin, *etal*, showed that in fact $K_L \Rightarrow 2\pi$ with a branching ratio on the order of 10^{-3}.



Interpretation:

CP Eigenstates

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K_0\rangle + |\overline{K_0}\rangle\right)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K_0\rangle - |\overline{K_0}\rangle\right)$$

Mass Eigenstates

$$|K_S\rangle \approx |K_1\rangle + \varepsilon|K_2\rangle$$

$$|K_L\rangle \approx |K_2\rangle + \varepsilon|K_1\rangle$$

$$\varepsilon = 2.3\times 10^{-3}$$

The Significance

In other words…

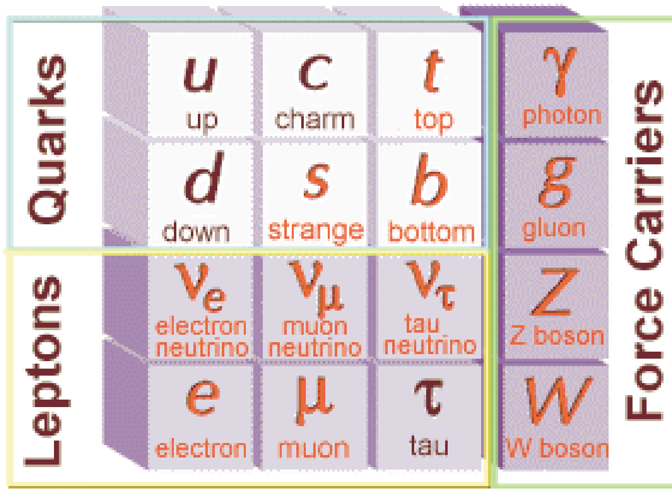
$$\left|K_{L,S}\right\rangle \equiv a_{L,S}\left|K^0\right\rangle + b_{L,S}\left|\overline{K^0}\right\rangle \quad \text{where} \quad \left|a_{L,S}\right| \neq \left|b_{L,S}\right|$$

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

Unlike parity violation, it is *not* trivial to incorporate CP violation into the standard model. To understand how it is done, we must now digress a bit into some details of fundamental particle interactions….

Weak Interactions in the Standard Model

- In the Standard Model, the fundamental particles are leptons and quarks



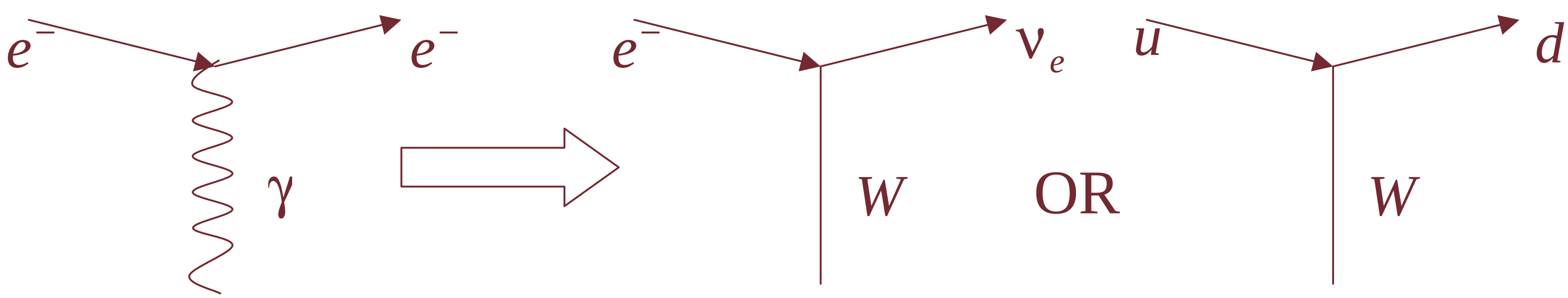
quarks combine as

qqq, $\overline{qqq}$, or $q\bar{q}$

to form hadrons

leptons exist independently

- In this model, weak interactions are analogous to QED.



Quark Mixing

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

In the Standard Model, leptons can only transition *within* a generation (NOTE: probably not true!)

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

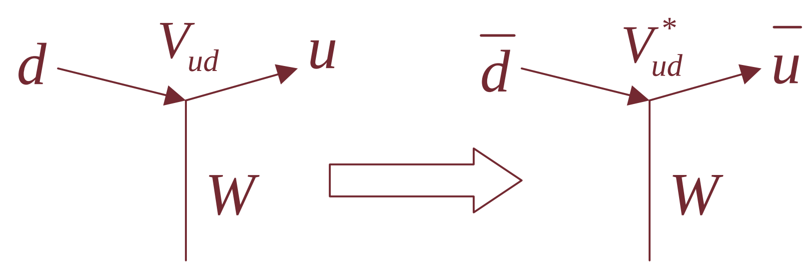
Although the rate is *suppressed*, quarks can transition *between* generations.

The CKM Matrix (1973)

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

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

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
- This requires at least three generations and led to prediction of *t* and *b* quarks … a year *before* the discovery of the c quark!

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"

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

First two generations *almost* unitary. λ= sine of "Cabbibo Angle"

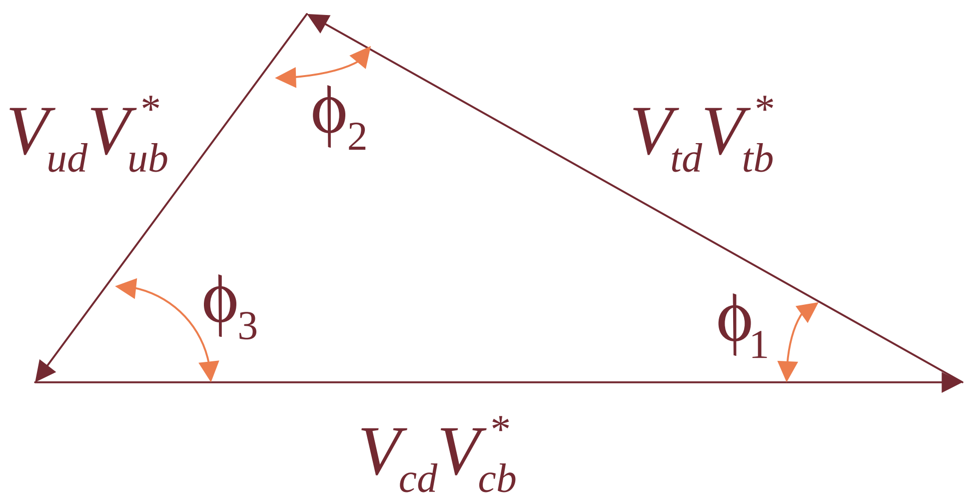
CP Violating phase

"The" Unitarity Triangle

- Unitarity imposes several constraints on the matrix, but one (product first and third columns)...

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

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



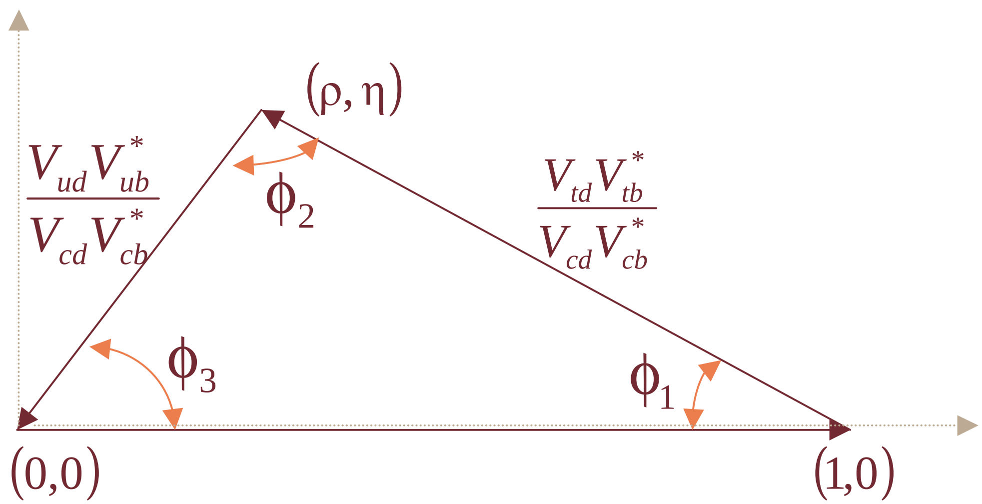
$$(\text{Note! in US}:\ \phi_1 \equiv \beta,\ \phi_2 \equiv \alpha,\ \phi_3 \equiv \gamma)$$

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 ($A\lambda^3$)….



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

Direct CP Violation in the Neutral Kaon System
(ε'/ε Measurement)

Recall…

$$|K_S\rangle = |K_1\rangle + \varepsilon |K_2\rangle$$
$$|K_L\rangle = |K_2\rangle + \varepsilon |K_1\rangle$$

If there is only *indirect* CP violation, then ALL 2π decays *really* come from K_1 , and we expect (among other things)

$$\frac{Br(K_L \Rightarrow \pi^+\pi^-)}{Br(K_L \Rightarrow \pi^0\pi^0)} = \frac{Br(K_1 \Rightarrow \pi^+\pi^-)}{Br(K_1 \Rightarrow \pi^0\pi^0)} = \frac{Br(K_S \Rightarrow \pi^+\pi^-)}{Br(K_S \Rightarrow \pi^0\pi^0)}$$

But the Standard Model allows

$$Br(K^0 \to 2\pi) \neq Br(\overline{K^0} \to 2\pi)$$
$$\Rightarrow K_2 \to 2\pi \longleftarrow \textit{Direct}\ \text{CP Violation}$$

Direct CP Violation in the Neutral Kaon System (cont'd)

Formalism:

CP=-1 CP=+1

$$|K_L\rangle = |K_2\rangle + \varepsilon |K_1\rangle$$

ε'

$$\pi\pi$$

CP=+1

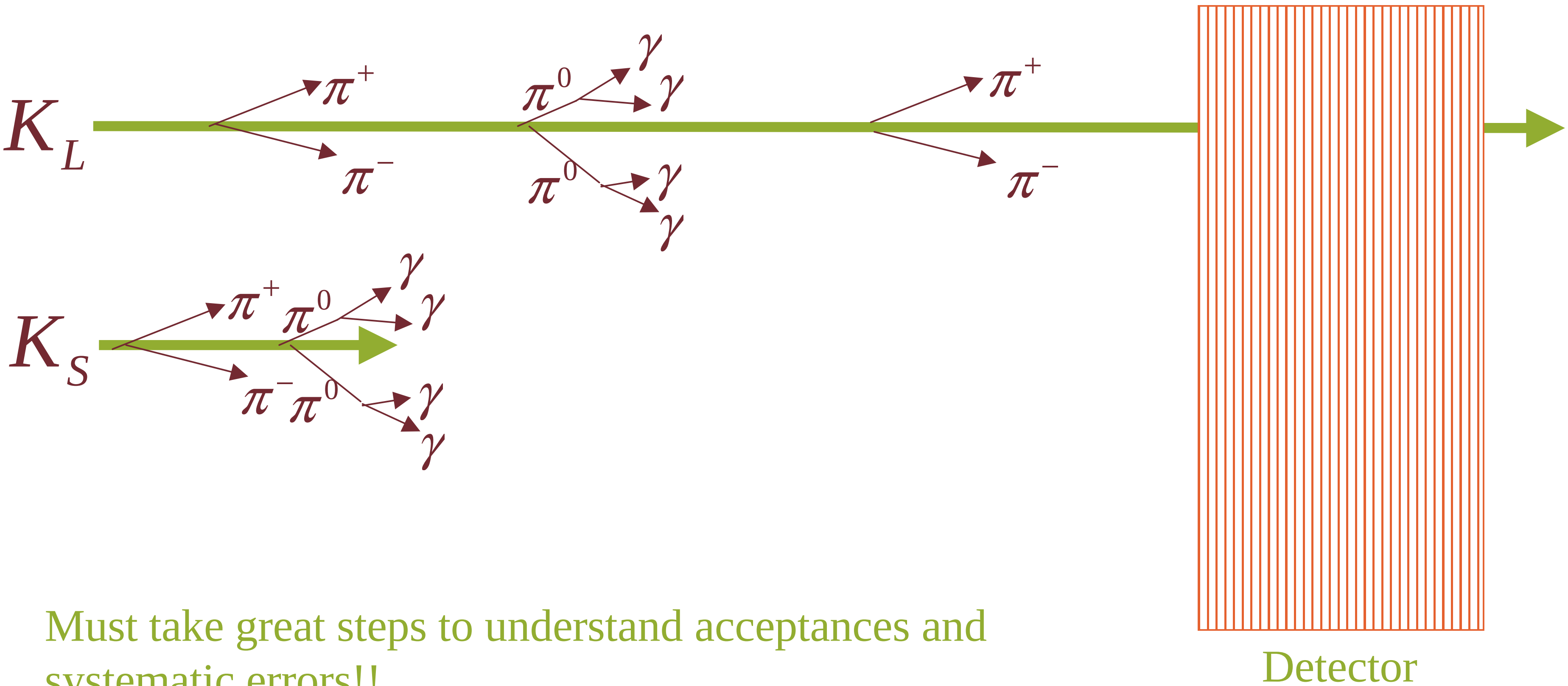
$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\frac{Br(K_L \to \pi^+\pi^-)/Br(K_S \to \pi^+\pi^-)}{Br(K_L \to \pi^0\pi^0)/Br(K_S \to \pi^0\pi^0)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \approx 1 + 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

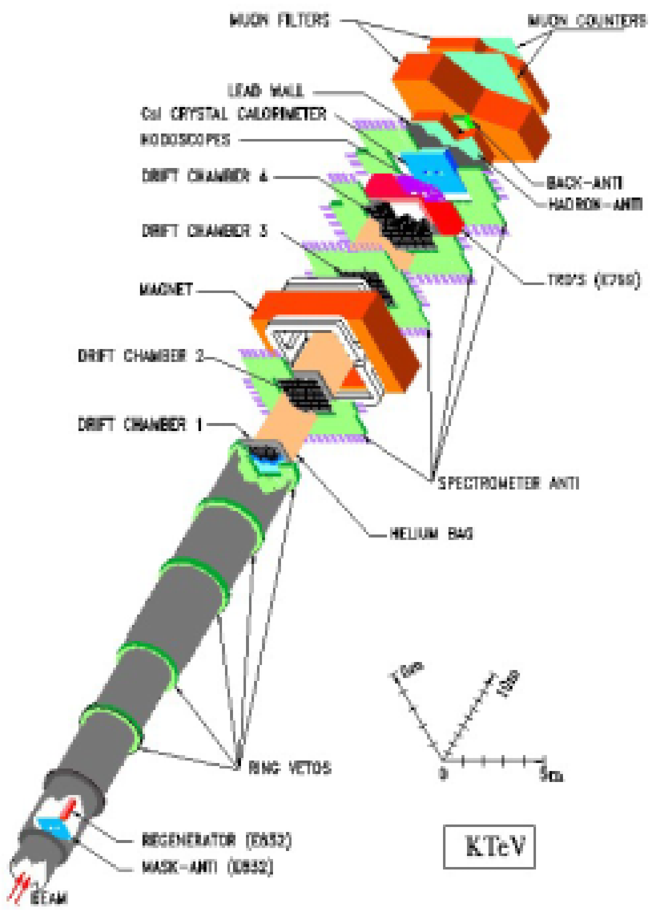
Theoretical estimates for ε'/ε range from $4\text{-}30 \times 10^{-4}$

Easy to Measure….NOT!



Must take great steps to understand acceptances and systematic errors!!

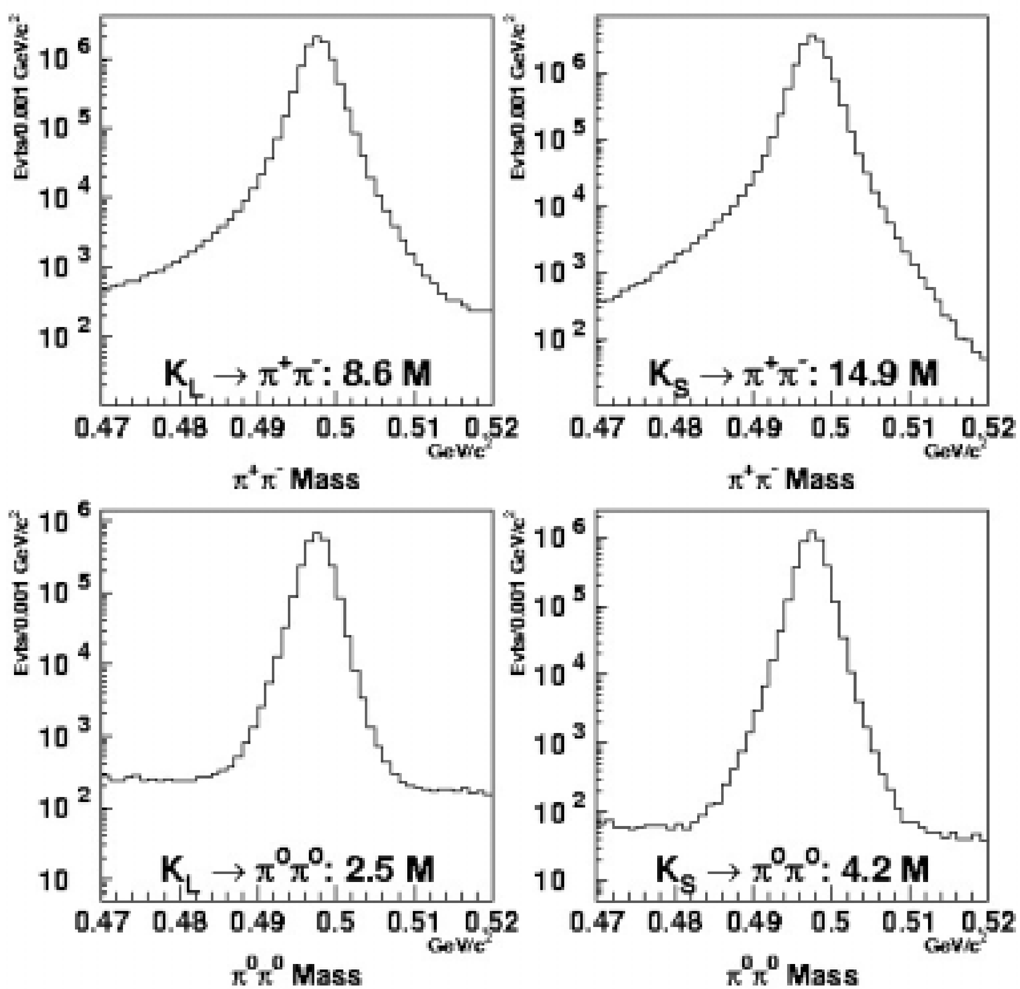
KTeV Experiment (Fermilab)



"Vacuum" beam $\rightarrow K_L$ beam

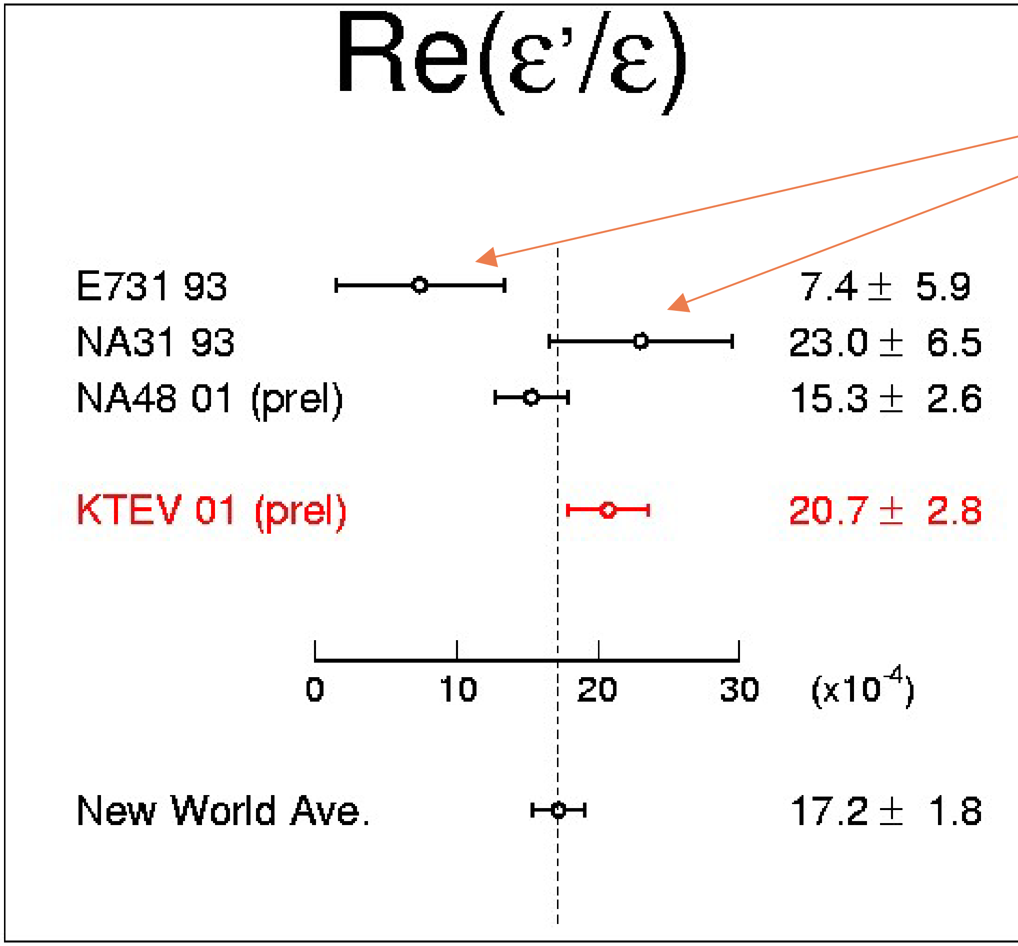
"Regenerator" beam $\rightarrow K_L + \rho K_S$ beam

No background subtraction



(Images from Jim Graham's Fermilab "Wine and Cheese" Talk)

Current Status of ε'/ε



$$\text{World Ave. Re}(\epsilon'/\epsilon) = 17.2 \pm 1.8 \times 10^{-4}$$
$$\text{Probability} = 13\%$$

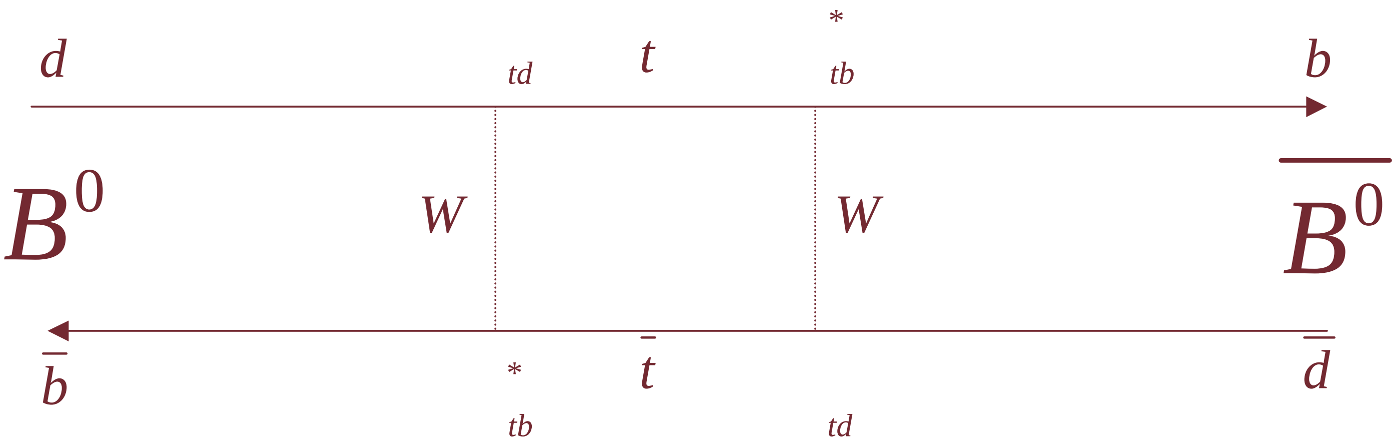
This bothered people

At this point, the accuracy of this measurement is better than that of the theoretical prediction:

($4\text{-}30 \times 10^{-4}$)

(ibid.)

- Let's Look at B-mixing…



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

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*

$$\begin{array}{ccc} B^0 & \longrightarrow & f \\ & \searrow \;\; \overline{B}^0 \;\; \nearrow & \end{array}$$

And the time-dependent decay probability will be

Difference between B mass eigenstates

$$P(t) = e^{-\Gamma|t|}[\{1 - \eta_{CP}\sin(\phi_M + \phi_D)\sin(\Delta m * t)\}]$$

CP state of *f*

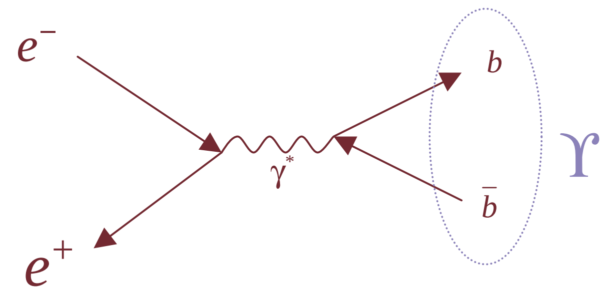
Mixing phase

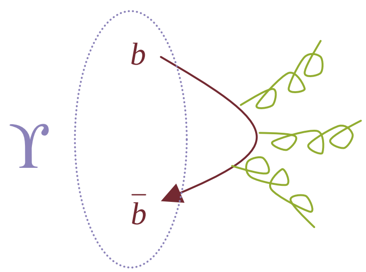
Decay phase

The Υ Resonances

At the right energies, electrons and positrons can produce a spectrum of bound resonant states of *b* and *anti-b* quarks

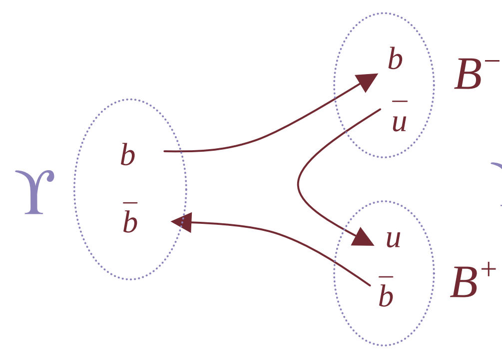
The 1⁻ states are called the "Υ ('Upsilon')resonances"

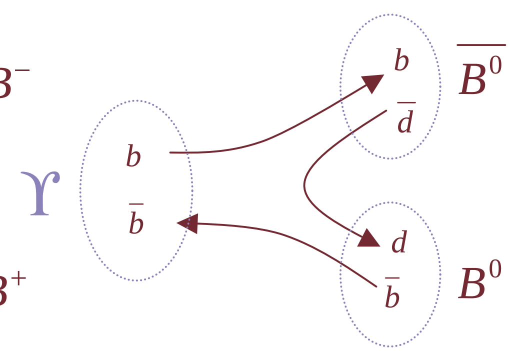




The lighter states must decay through quark-antiquark annihilation

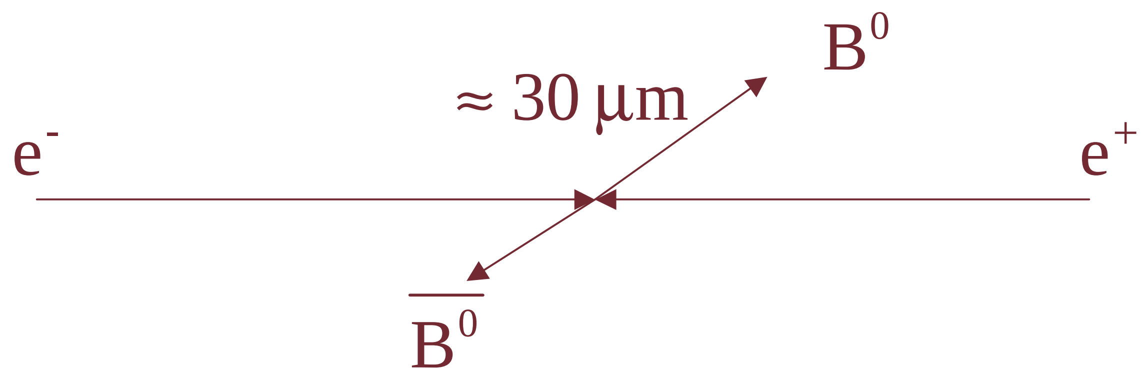
Starting with the Υ(4S), they can decay strongly to pairs of B-mesons.





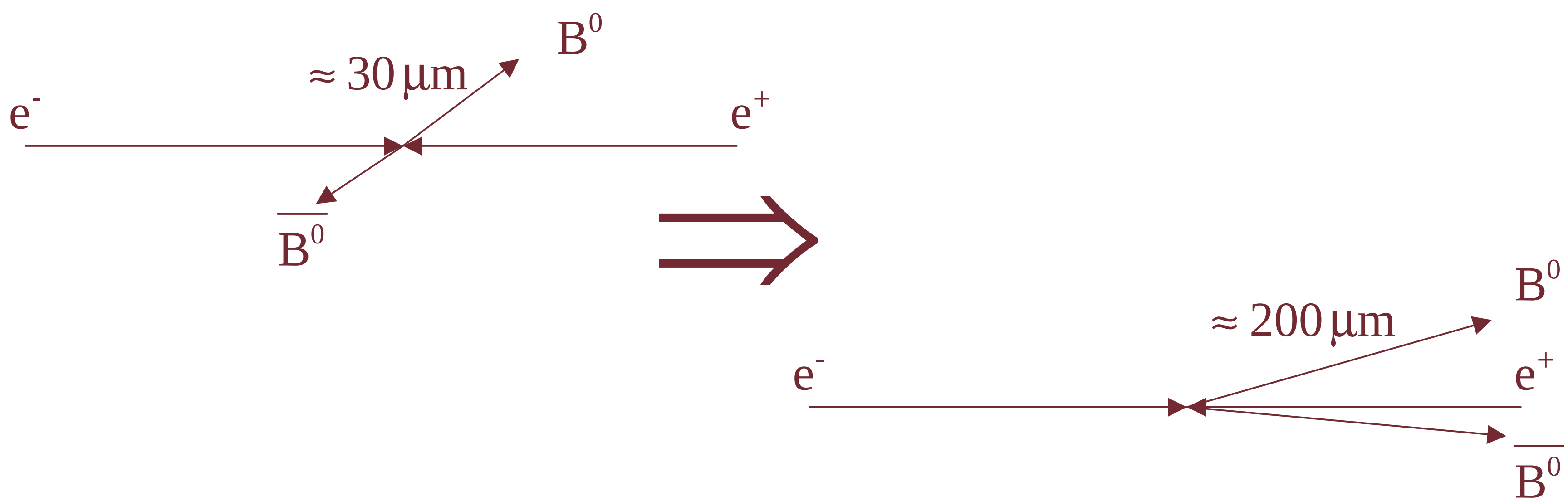
The Basic Idea

- 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.

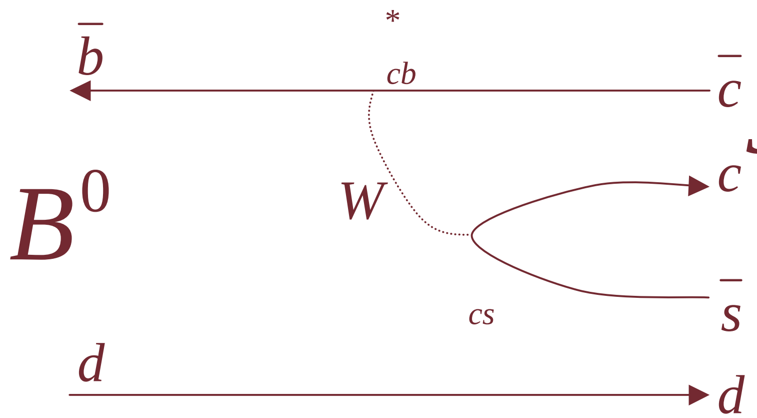


The Clever Trick (courtesy P. Oddone)

- 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

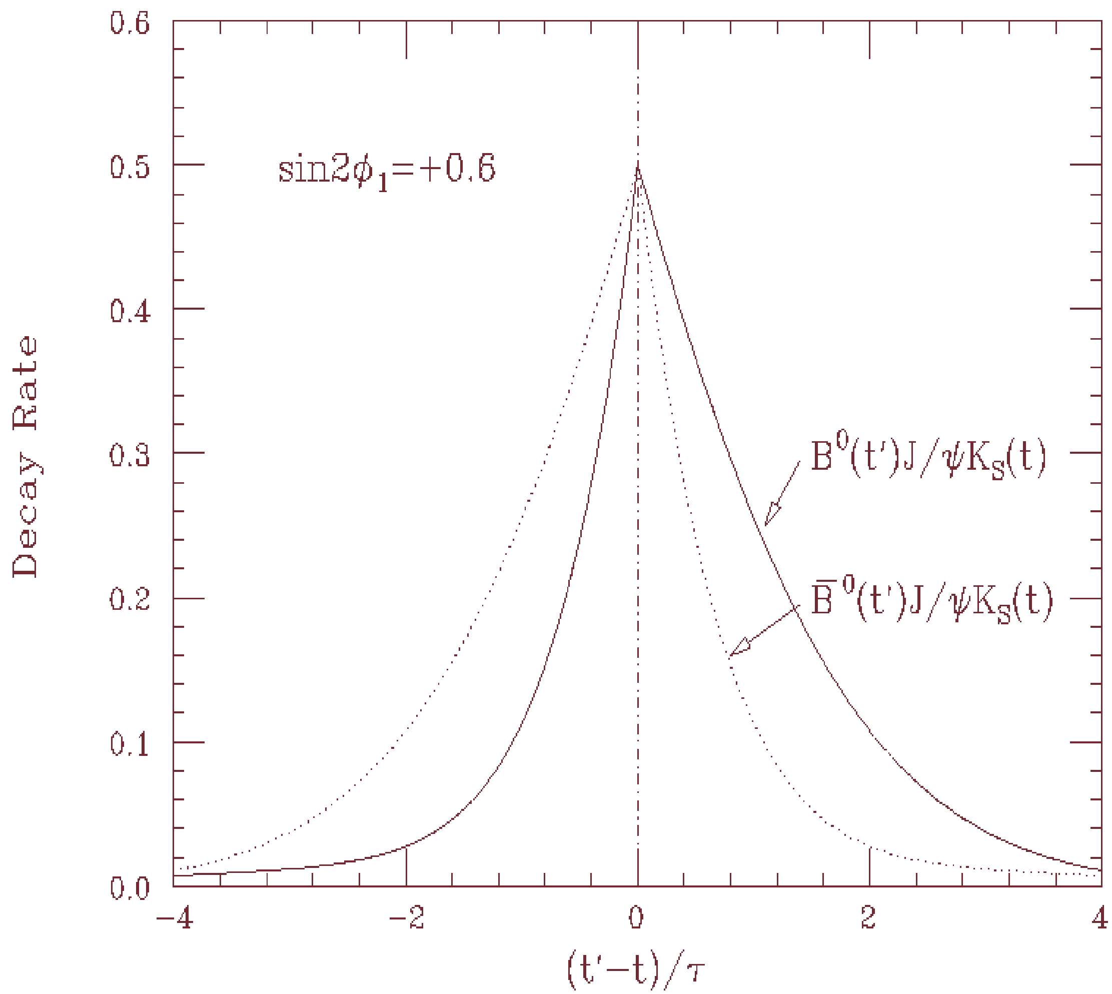
$$K_S(CP = -1), K_L(CP = +1)$$

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

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

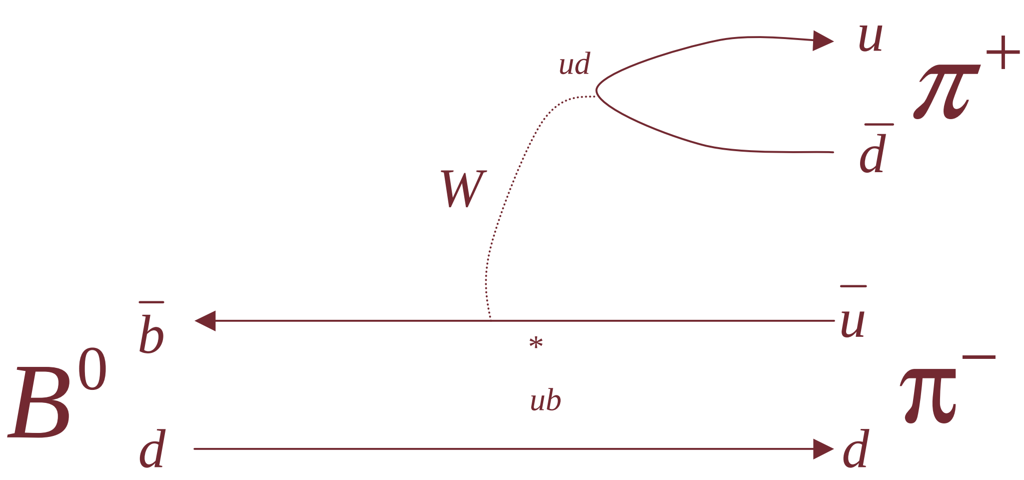
$$\text{probes } \phi_M = \phi_1 \ (= \beta)$$

Predicted Signature



t = Time of tagged decays

"Tin-Plated" Decay



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

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

Complicated by "penguin pollution", but still promising

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

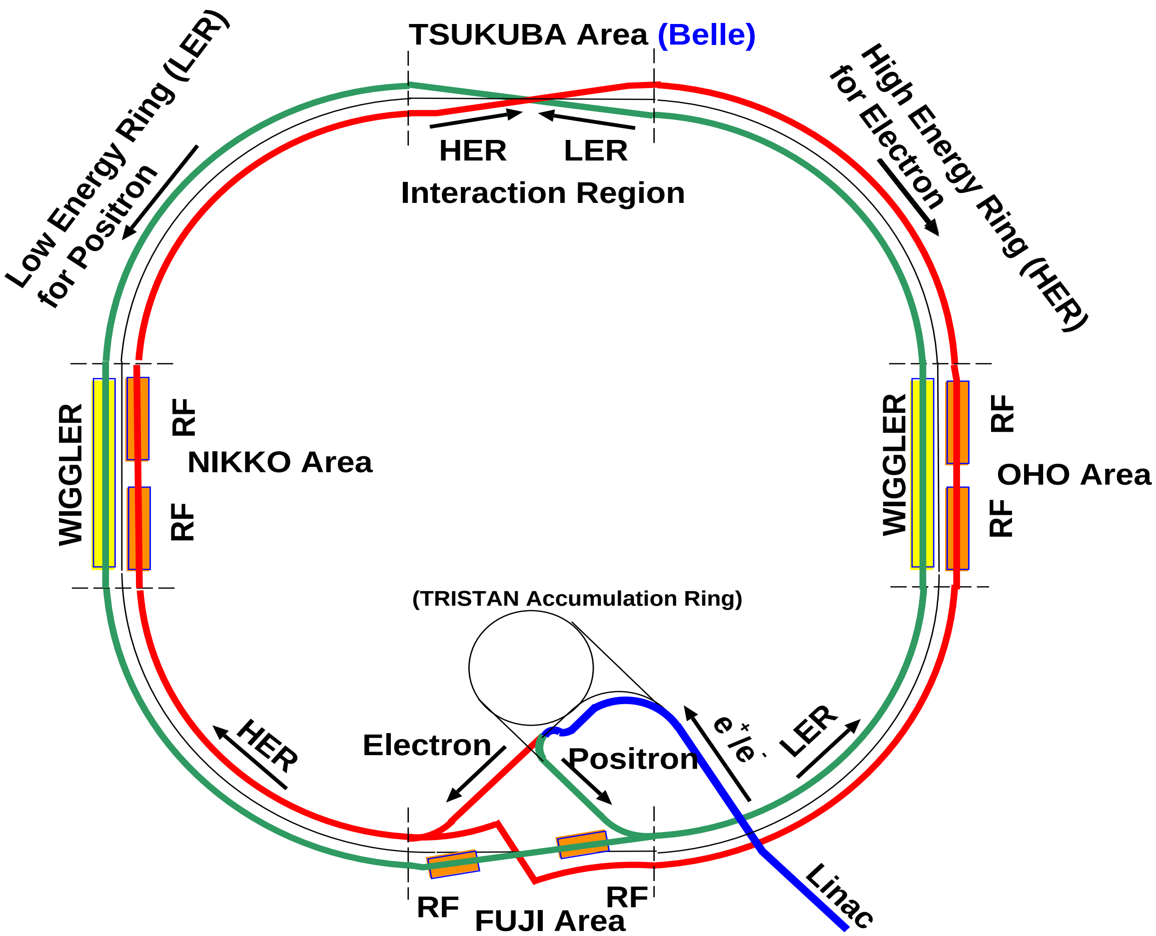
$$e^{-\Gamma|t|}\left[\left\{1 - \eta_{CP} \sin 2\phi_1 \sin \Delta m \Delta t\right\}\right]$$

- Write papers.
- Over the last ~8 years, there have been two dedicated experiments under way to do this – BaBar (SLAC) and Belle (KEK)

Motivations for Accelerator Parameters

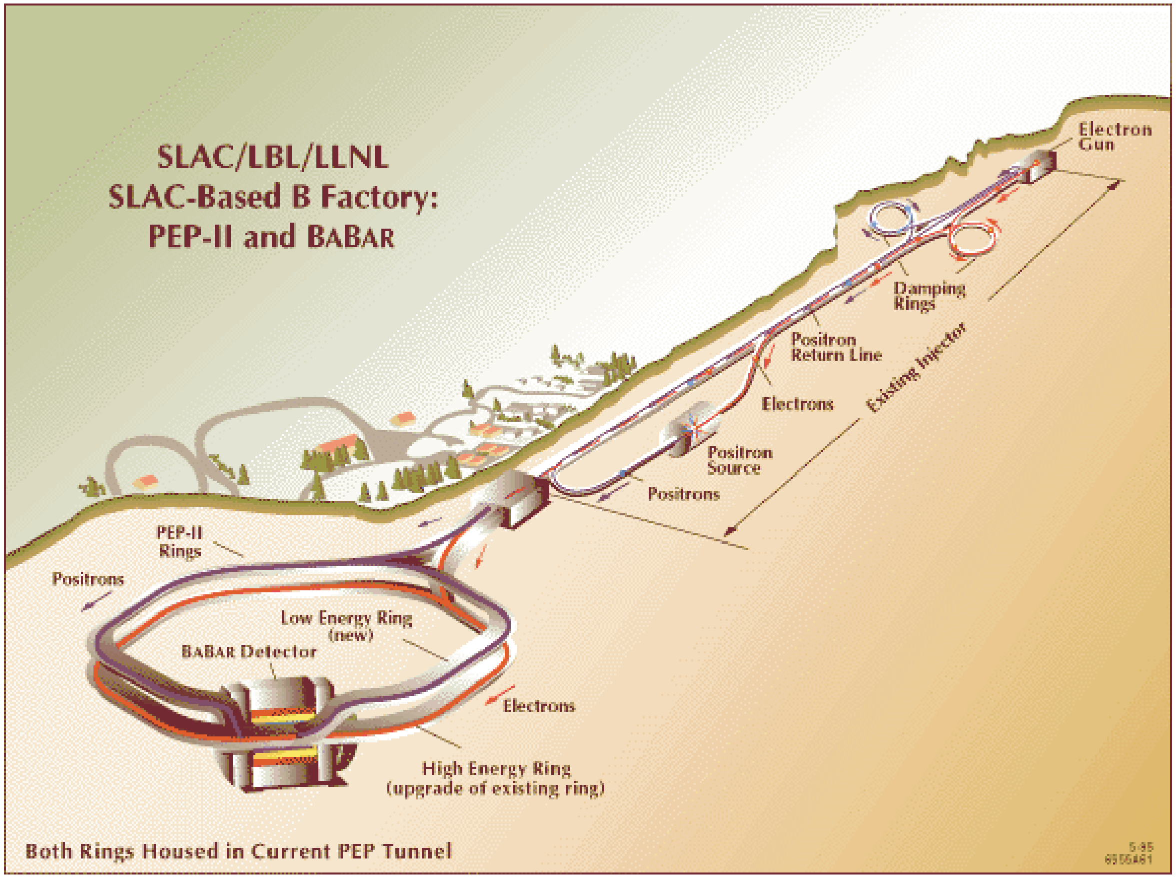
- Must be asymmetric to take advantage of Lorentz boost.
- The decays of interest all have branching ratios on the order of 10^{-5} or lower.
  - Need lots and lots of data!
    - Physics projections assume $100\ fb^{-1} = 1yr\ @\ 10^{34}\ cm^{-2}s^{-1}$
    - Would have been pointless if less than $10^{33}\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

The KEKB Collider (KEK)



- 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

The PEP-II Collider (SLAC)



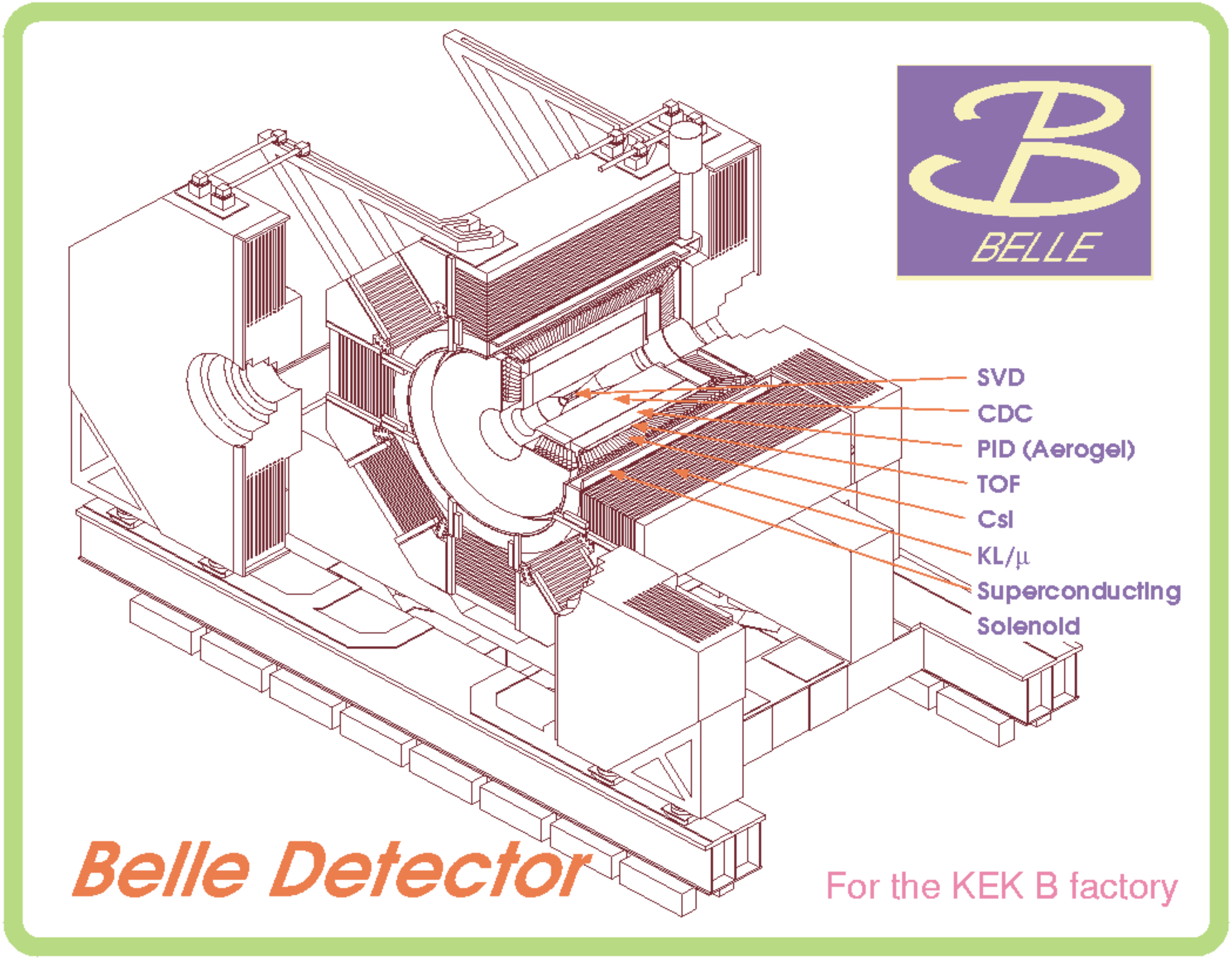
- Asymmetric Rings
  - 9.0GeV(HER)
  - 3.1GeV(LER)
- E_{cm}=10.58GeV= M(ϒ(4S))
- Target Luminosity: $3\text{x}10^{33}s^{-1}cm^{-2}$
- Crossing angle: 0 mr
- 4ns crossing time

Motivation for Detector Parameters

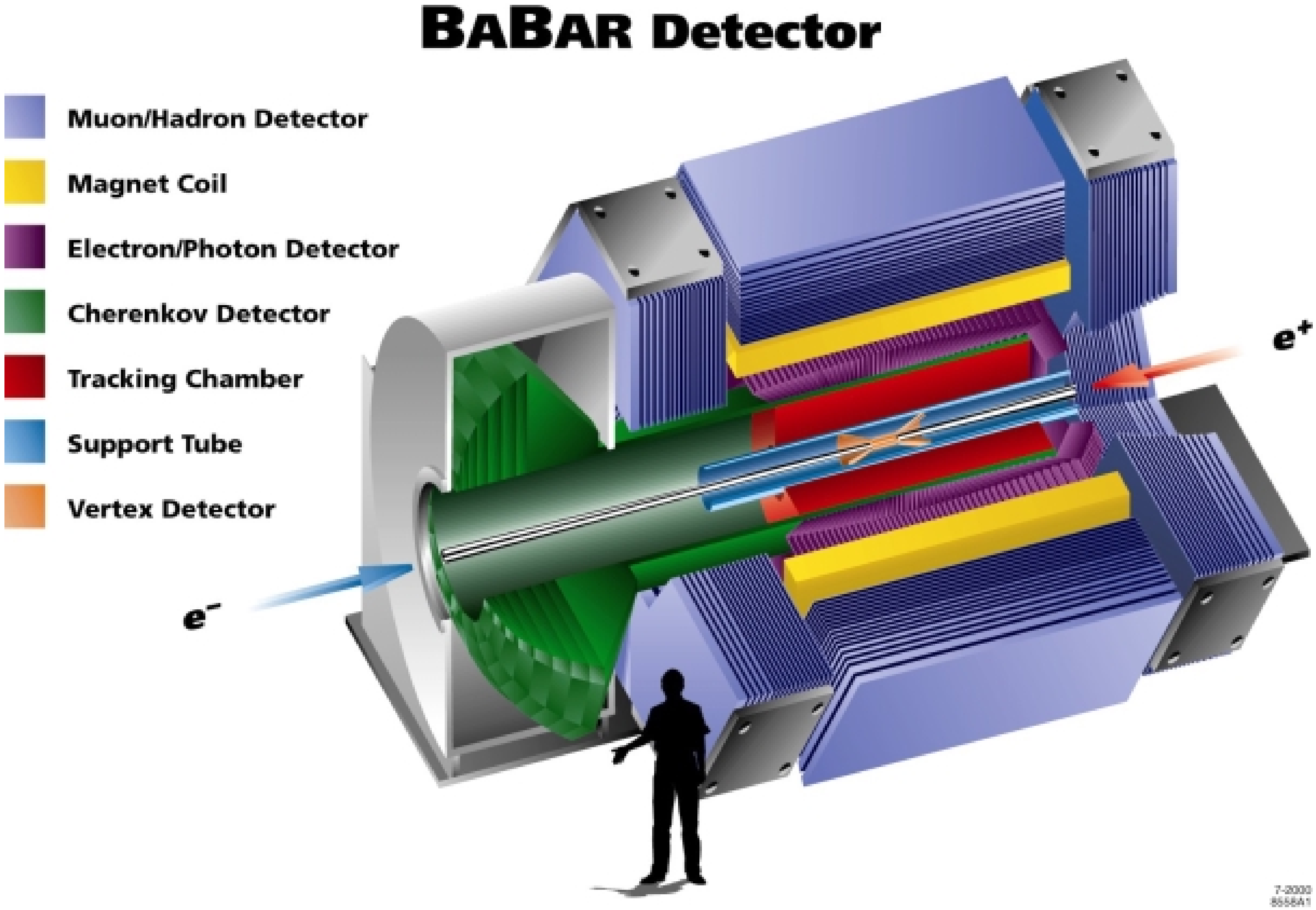
- Vertex Measurement
  - Need to measure decay vertices to $<100\mu m$ to get proper time distribution.
- Tracking…
  - Would like $\Delta p/p \approx .5\text{-}1\%$ to help distinguish $B \rightarrow \pi\pi$ decays from $B \rightarrow K\pi$ and $B \rightarrow KK$ decays.
  - Provide dE/dx for particle ID.
- EM calorimetry
  - Detect γ's from slow, asymmetric π^0's $\rightarrow$ need efficiency down to 20 MeV.
- Hadronic Calorimetry
  - Tag muons.
  - Tag direction of K_L's from decay $B \rightarrow \psi K_L$.
- Particle ID
  - Tag strangeness to distinguish B decays from Bbar decays (low p).
  - Tag π's to distinguish $B \rightarrow \pi\pi$ decays from $B \rightarrow K\pi$ and $B \rightarrow KK$ decays (high p).

Rely on mature, robust technologies whenever possible!!!

The Belle Detector



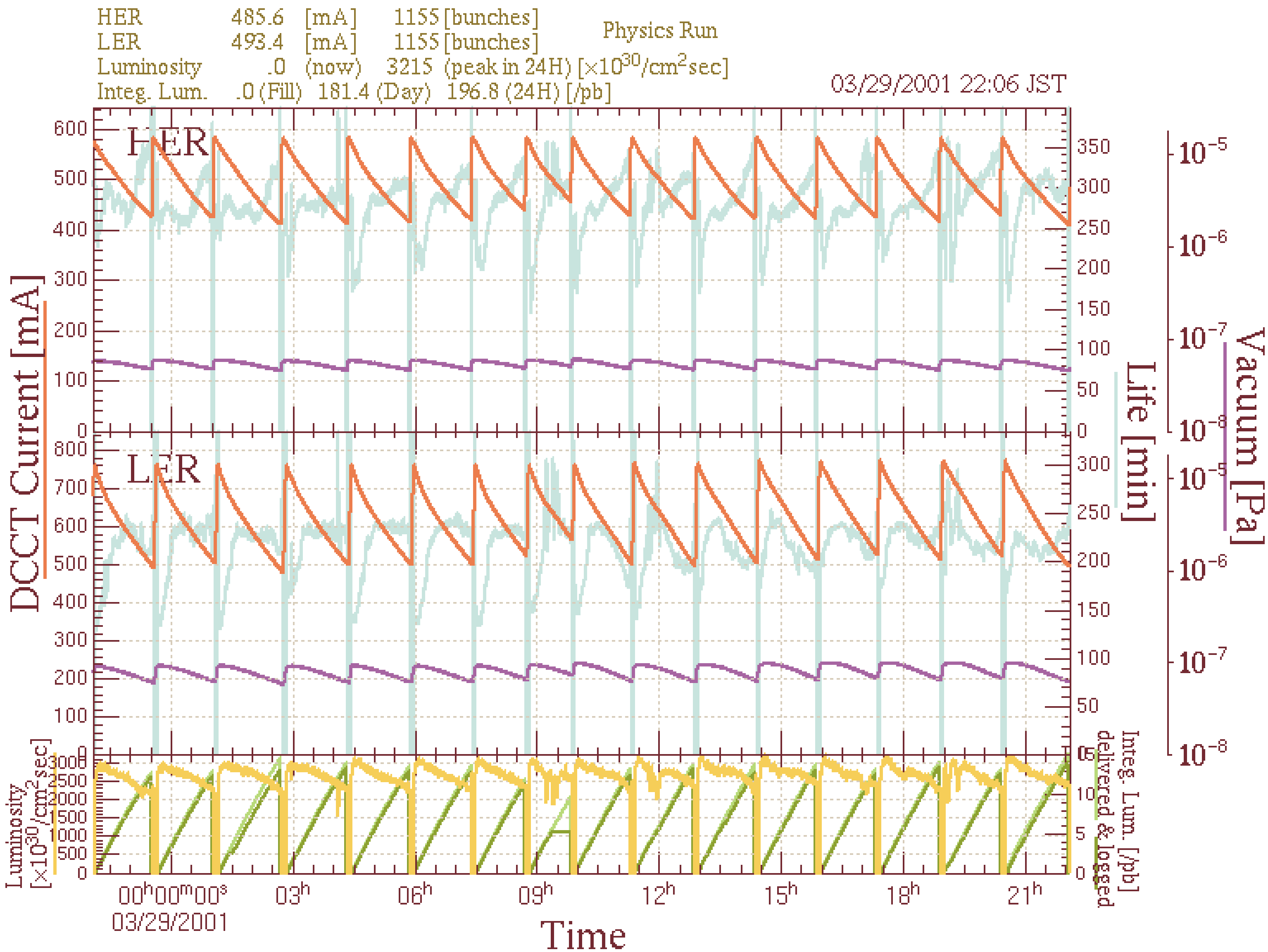
BaBar Detector (SLAC)



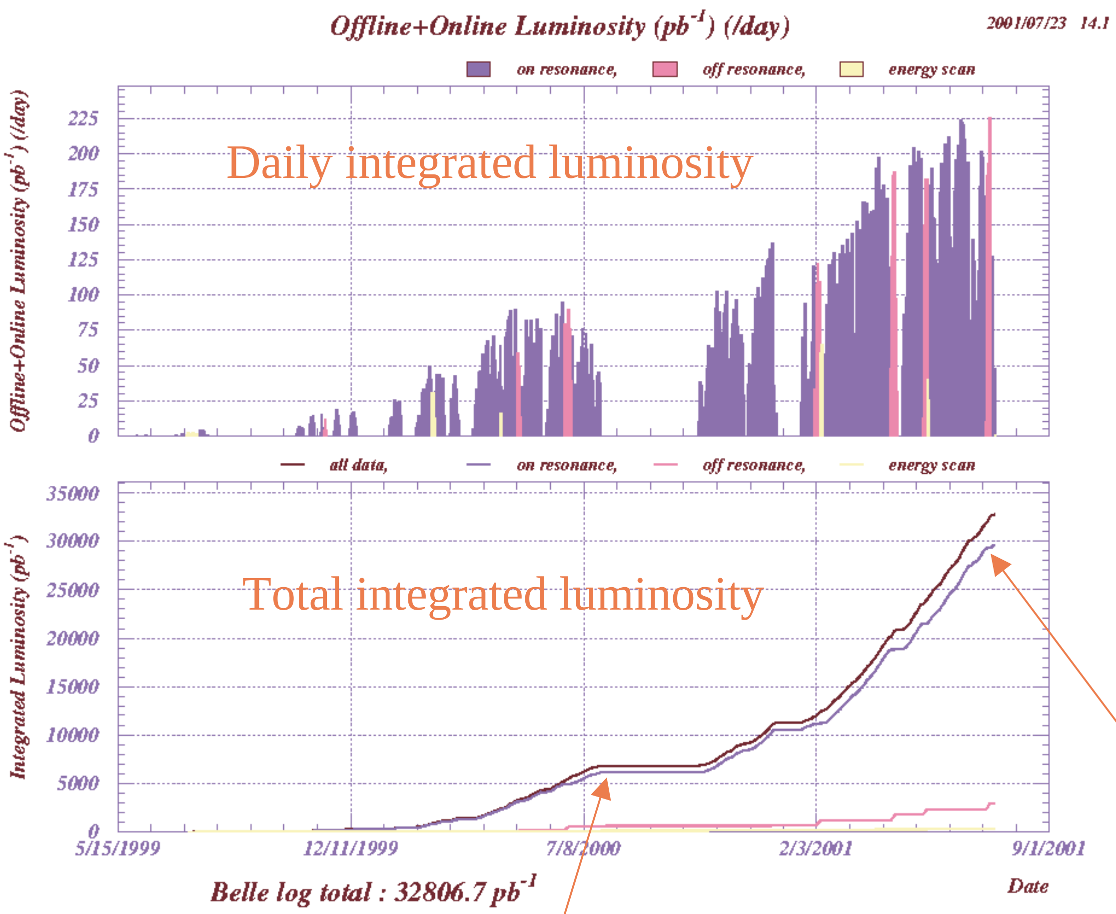
The Accelerator is Key!!!

STOP Run
+HV Down
+Fill HER
+Fill LER
+HV Up
+START Run

= 8 Minutes!



Luminosity



Our Records:

World Records!!

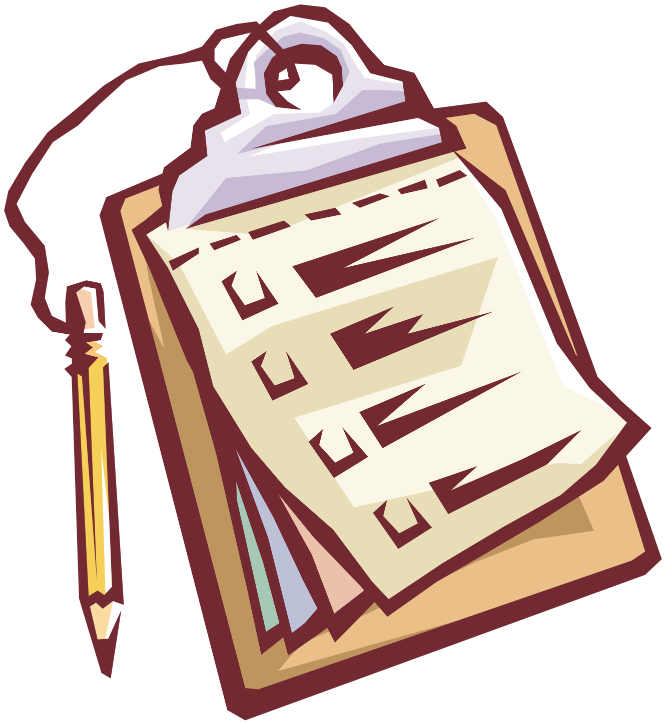
- Instantaneous: 4.49×10^{33} cm^{-2}s^{-1}
- Per (0-24h) day: 229.1 pb^{-1}
- Per (24 hr) day: 241.3 pb^{-1}
- Per week: 1478 pb^{-1}
- To date: $\approx$ 29.9 fb^{-1} (on peak)

Note: integrated numbers are accumulated!

Total for *these* Results: 29.1 fb^{-1}

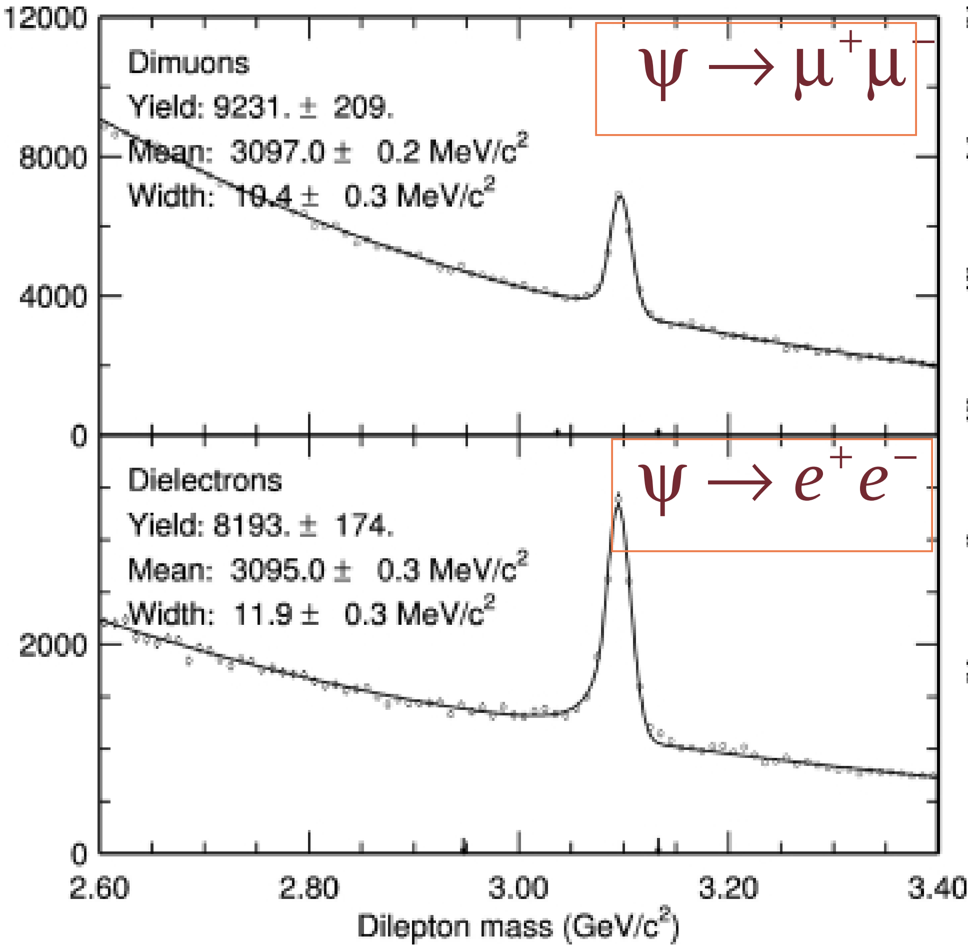
Total for first CP Results (Osaka): 6.2 fb^{-1}

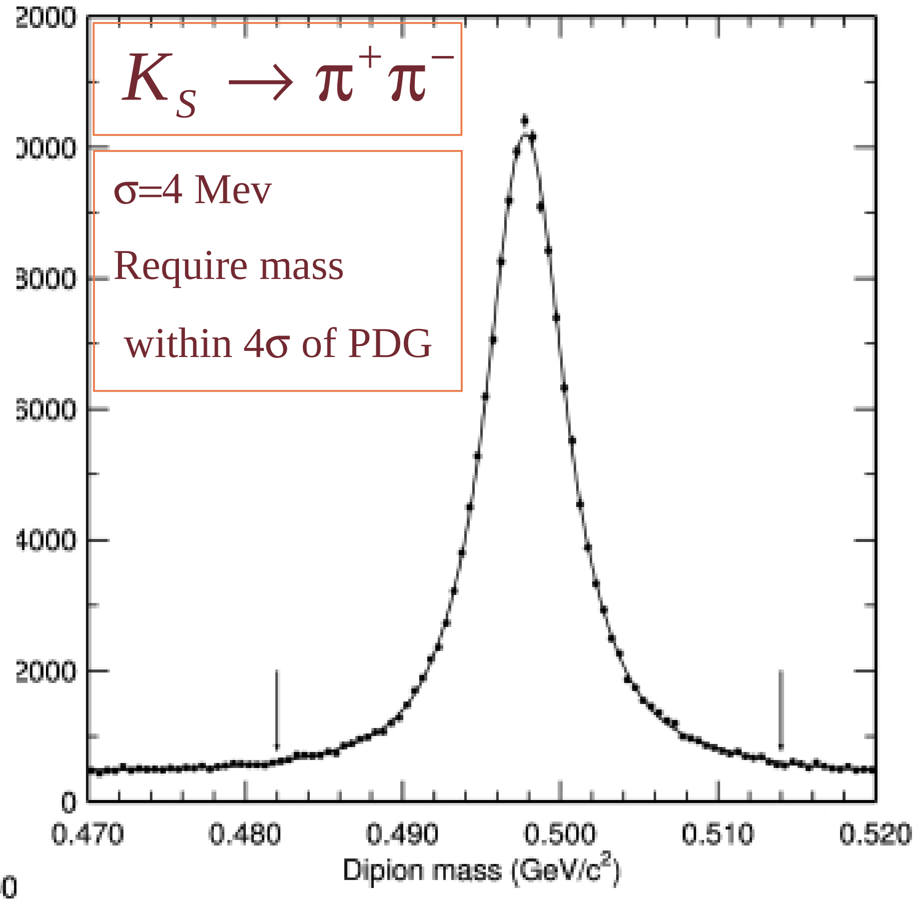
The Pieces of the Analysis



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

J/ψ and K_S Reconstruction





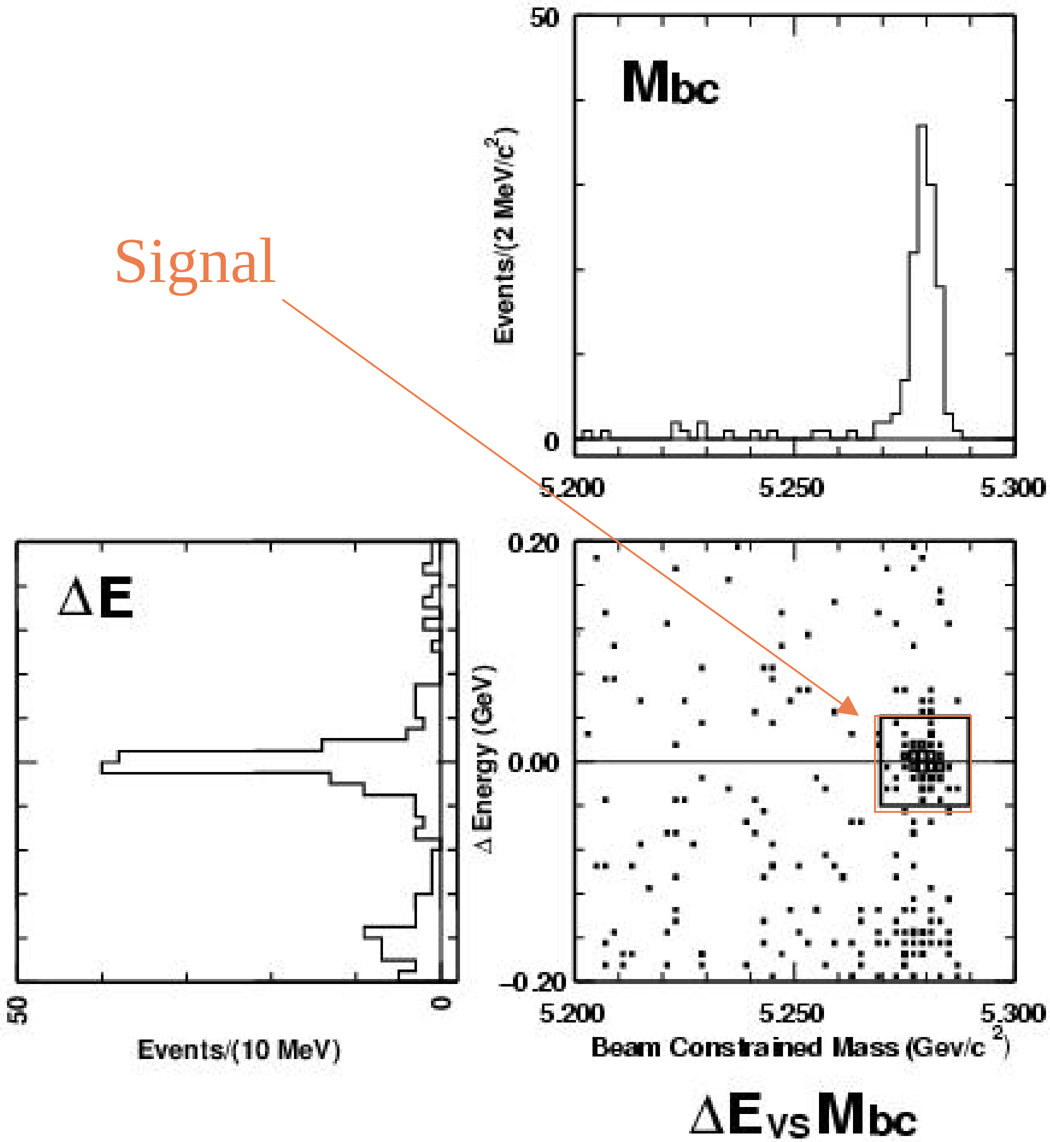
$B \to \psi K_S$ Reconstruction

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

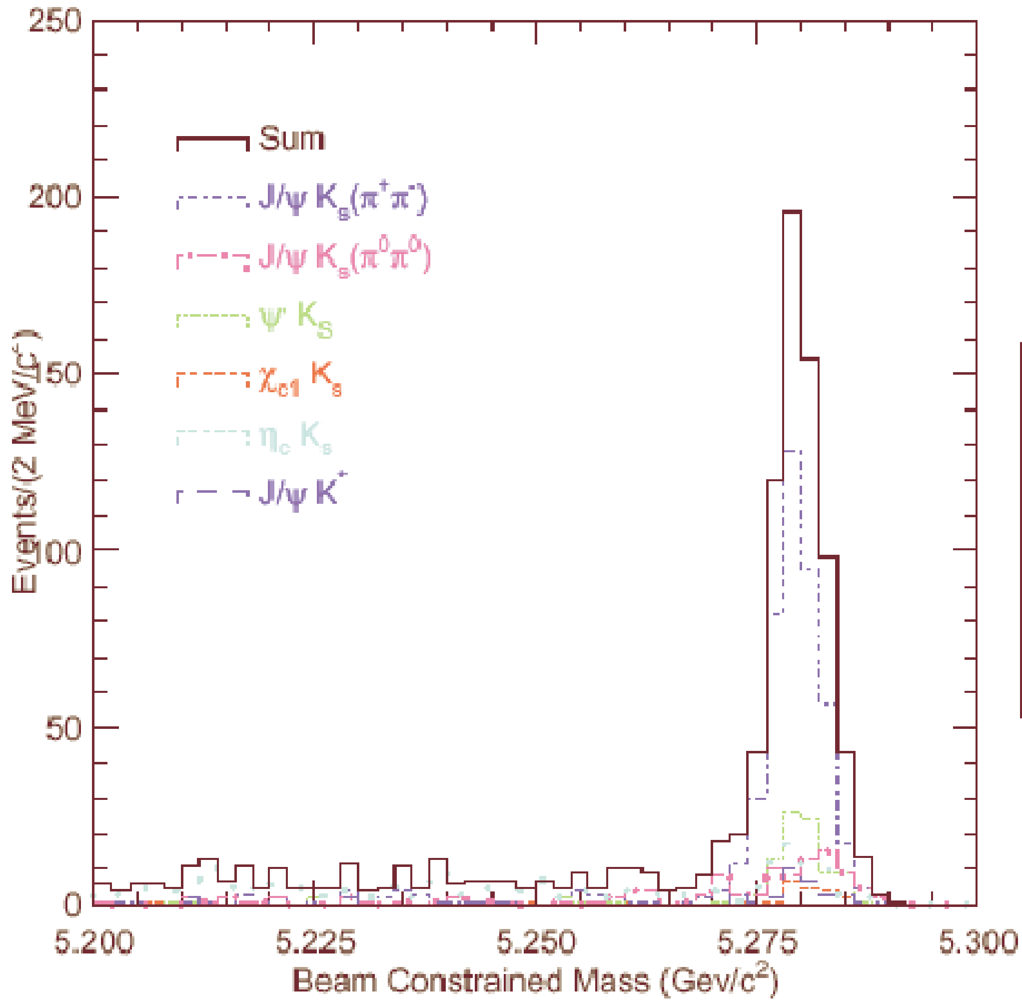
$$M_{BC}^2 = E_{beam}^2 - \left(\sum \vec{p}\right)^2$$

123 Events

3.7 Background

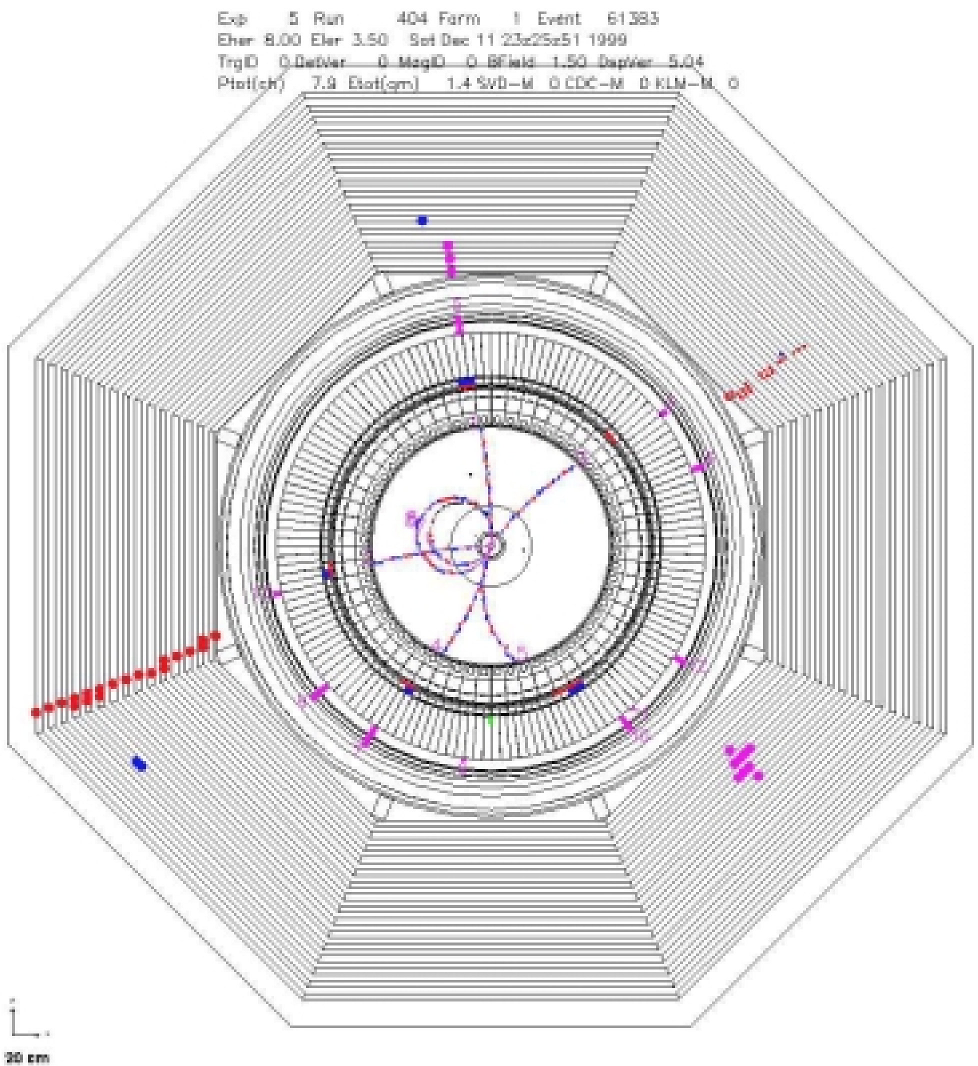


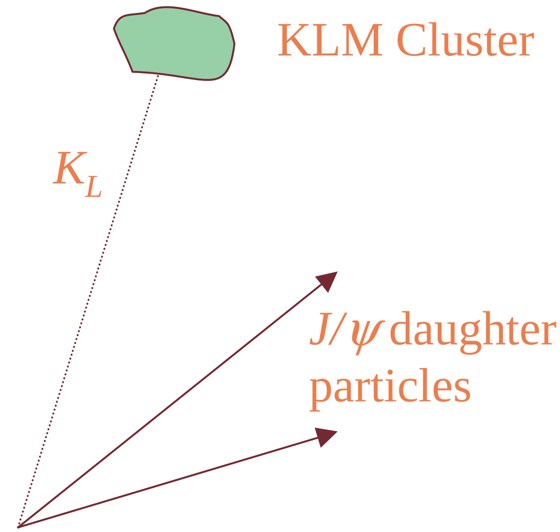
All Fully Reconstructed Modes (i.e. all but ψK_L)



Mode	Events	Background
$B \rightarrow \psi K_S$	457	12
All Others	290	46
Total	747	58

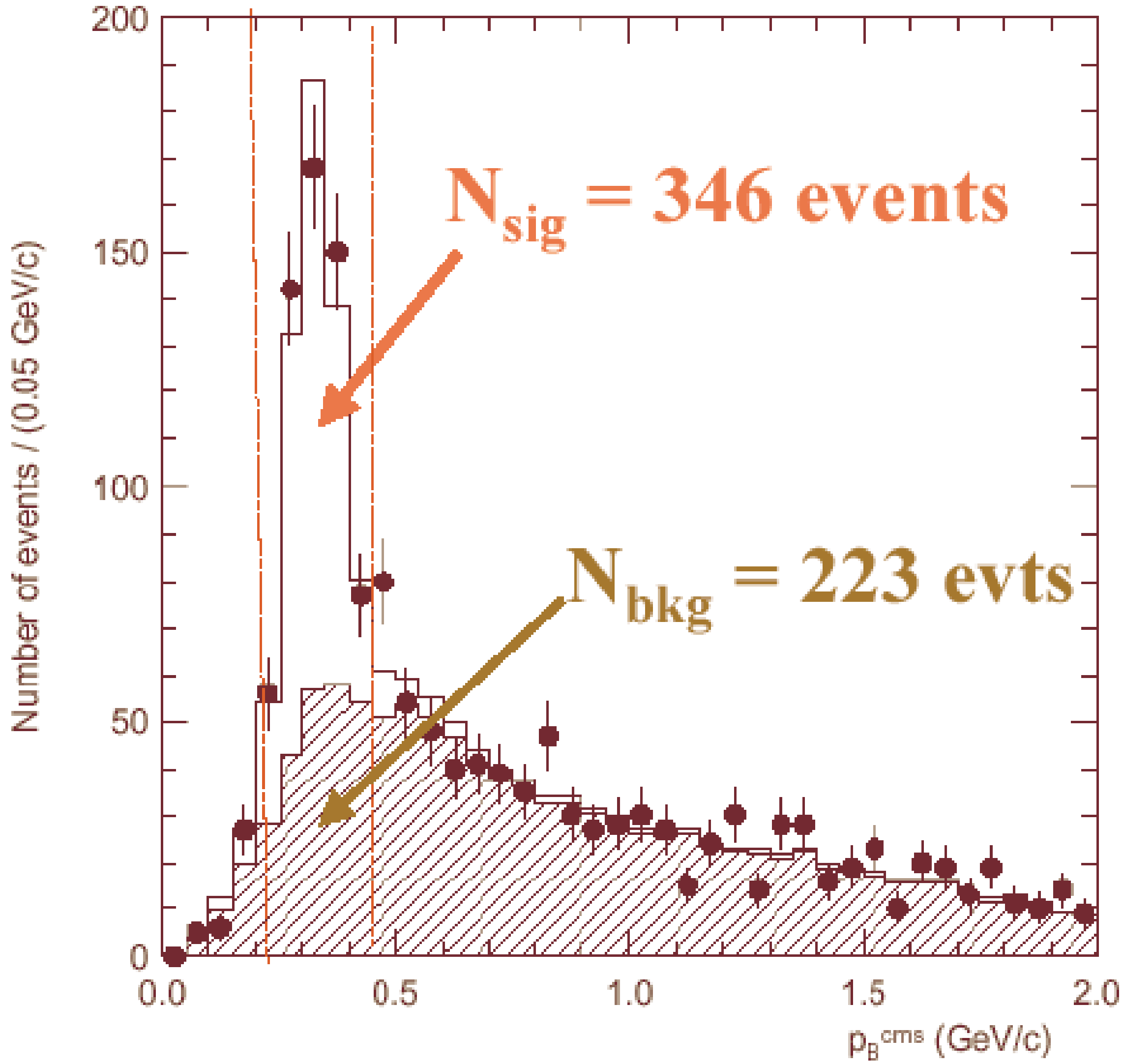
$B \rightarrow \psi K_L$ Reconstruction





- 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



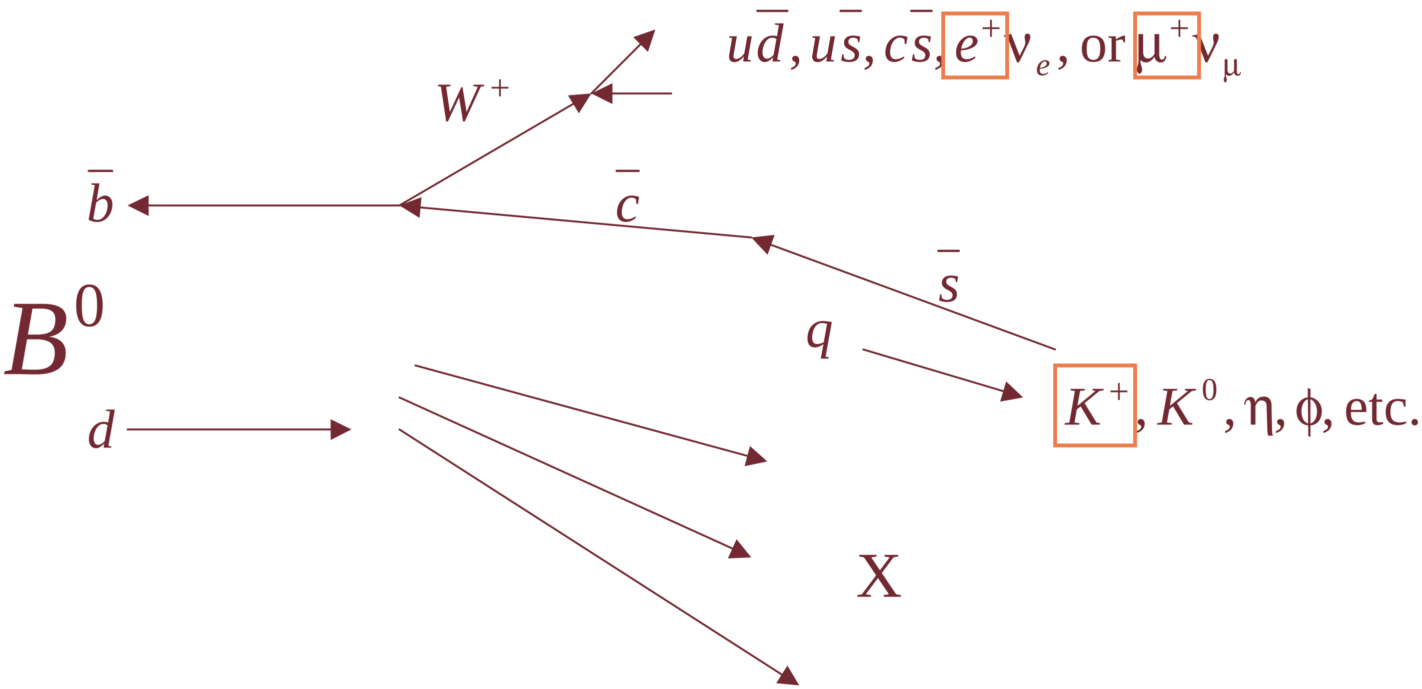
$0 < p_B^* < 2$ GeV/c

Biases spectrum!

346 Events

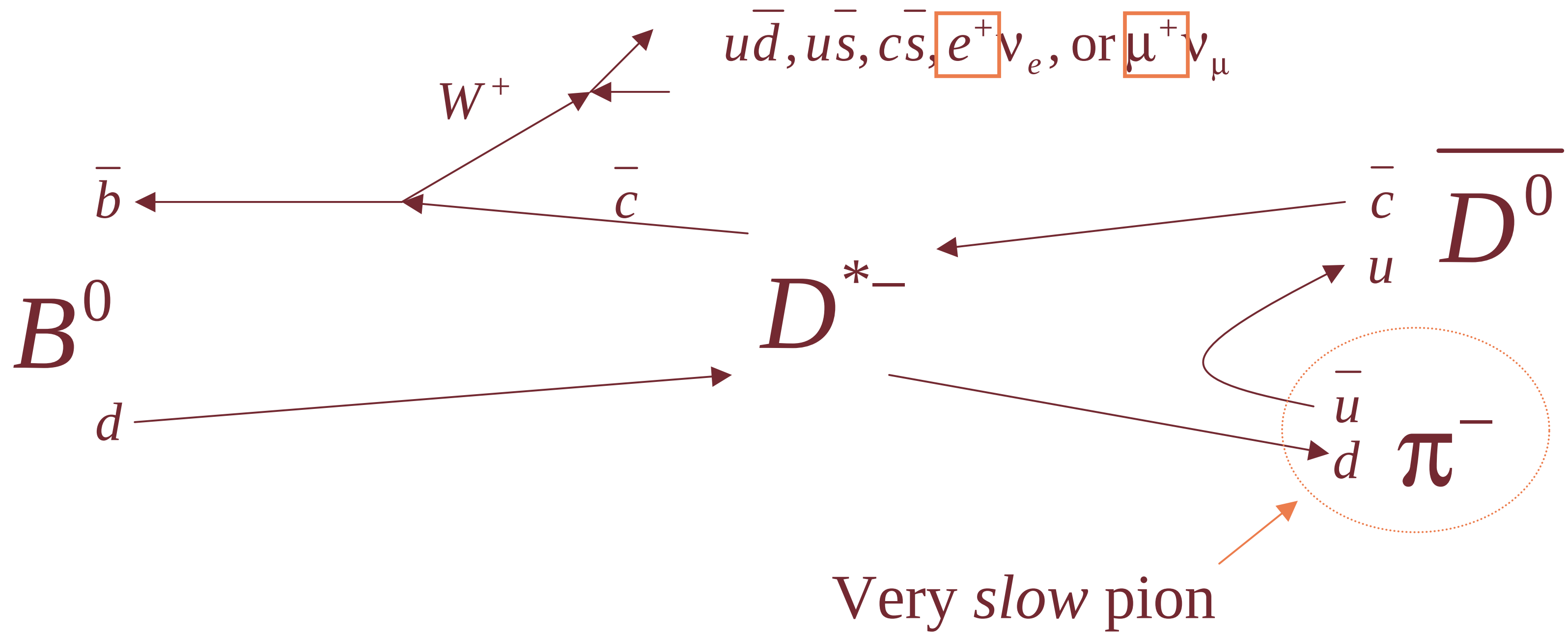
223 Background

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.

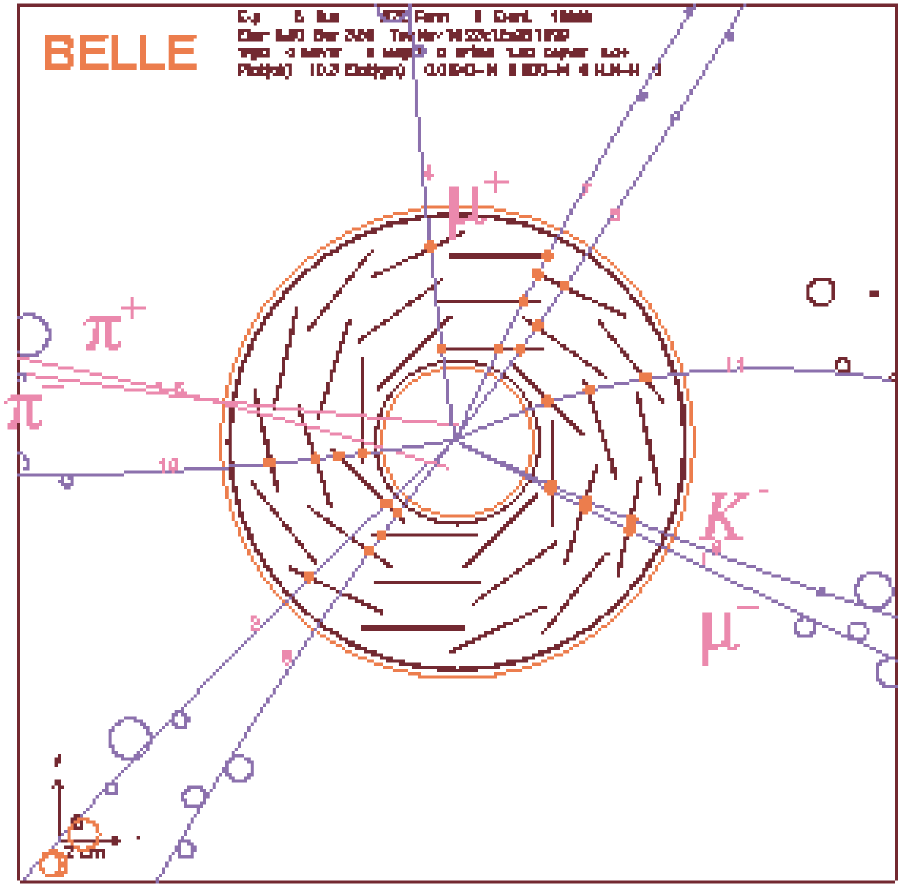
Flavor Tagging (Slow Pion)



B^0's will tend to produce slow π^-.

Combined effective efficiency $\varepsilon_{eff} = \varepsilon_t(1\text{-}2w)^2 = 27.0\pm.2\%$

Vertex Reconstruction (SVD)



Overall efficiency = ~85%. In total 1137 events for the CP fit.

CP Fit (Probability Density Function)

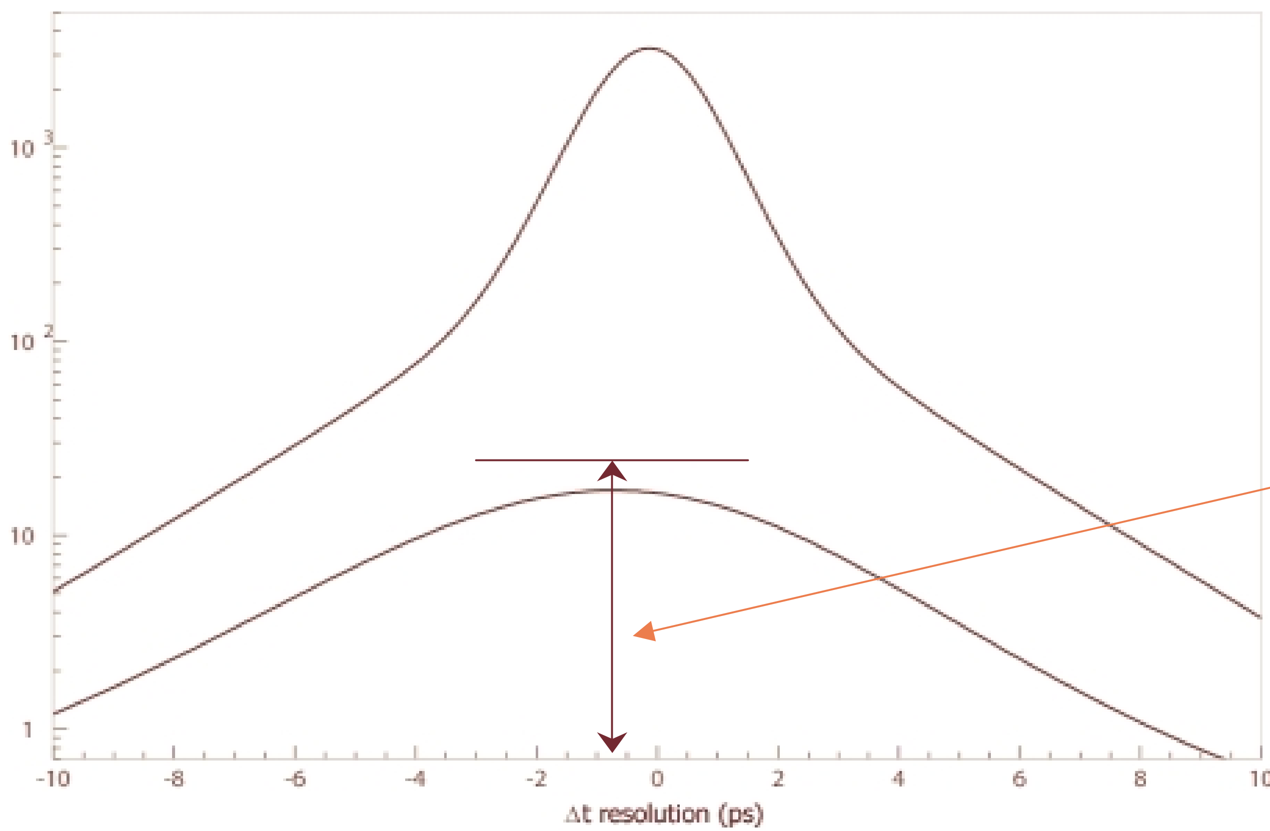
$$f(\Delta t;\sin 2\phi_1) = \mathrm{e}^{-\frac{|\Delta t|}{\tau_B}}\left(1 \pm \sin 2\phi_1 \sin x_d \frac{\Delta t}{\tau_B}\right)$$

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

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

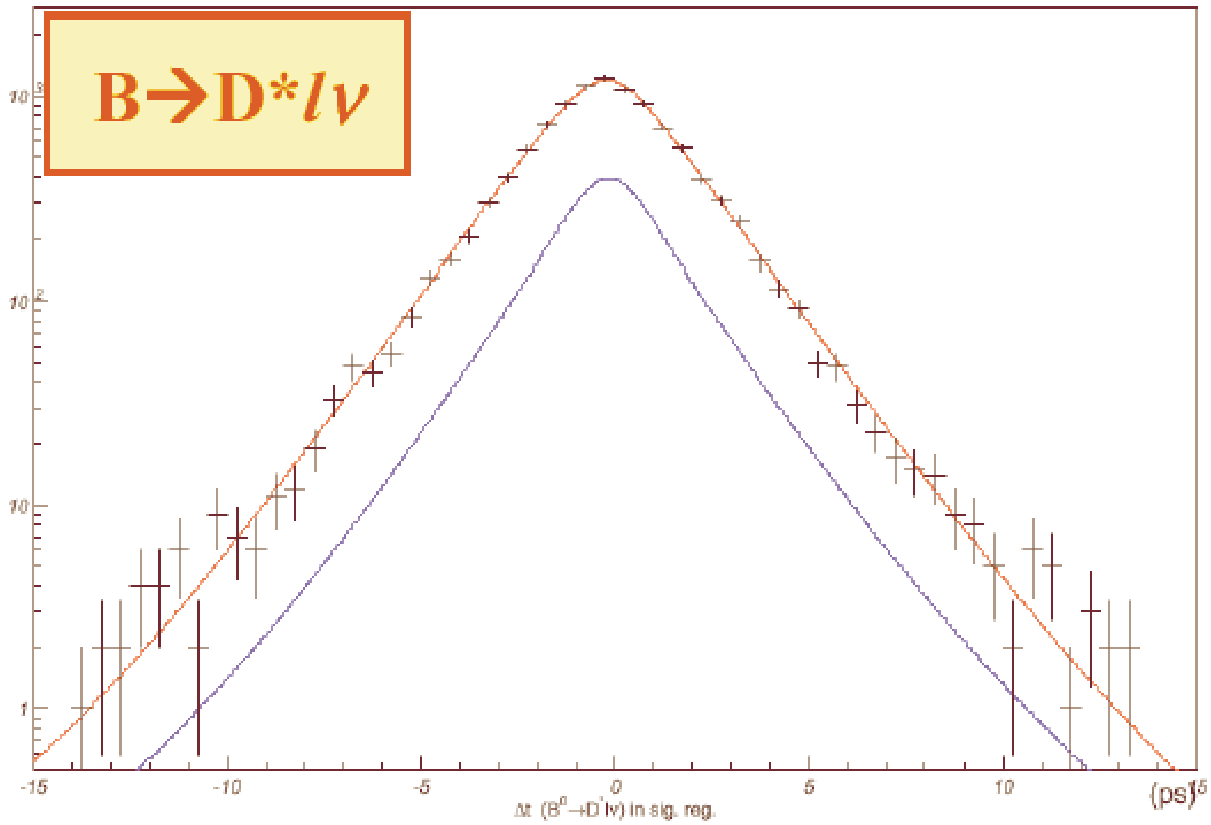
Resolution Function

Fit with a double-Gaussian…



$$\mu_{main} \quad -0.09\ \text{ps}$$
$$\sigma_{main} \quad 1.54\ \text{ps}$$
$$\mu_{tail} \quad -0.78\ \text{ps}$$
$$\sigma_{tail} \quad 3.78\ \text{ps}$$
$$f_{tail} \quad 0.018$$

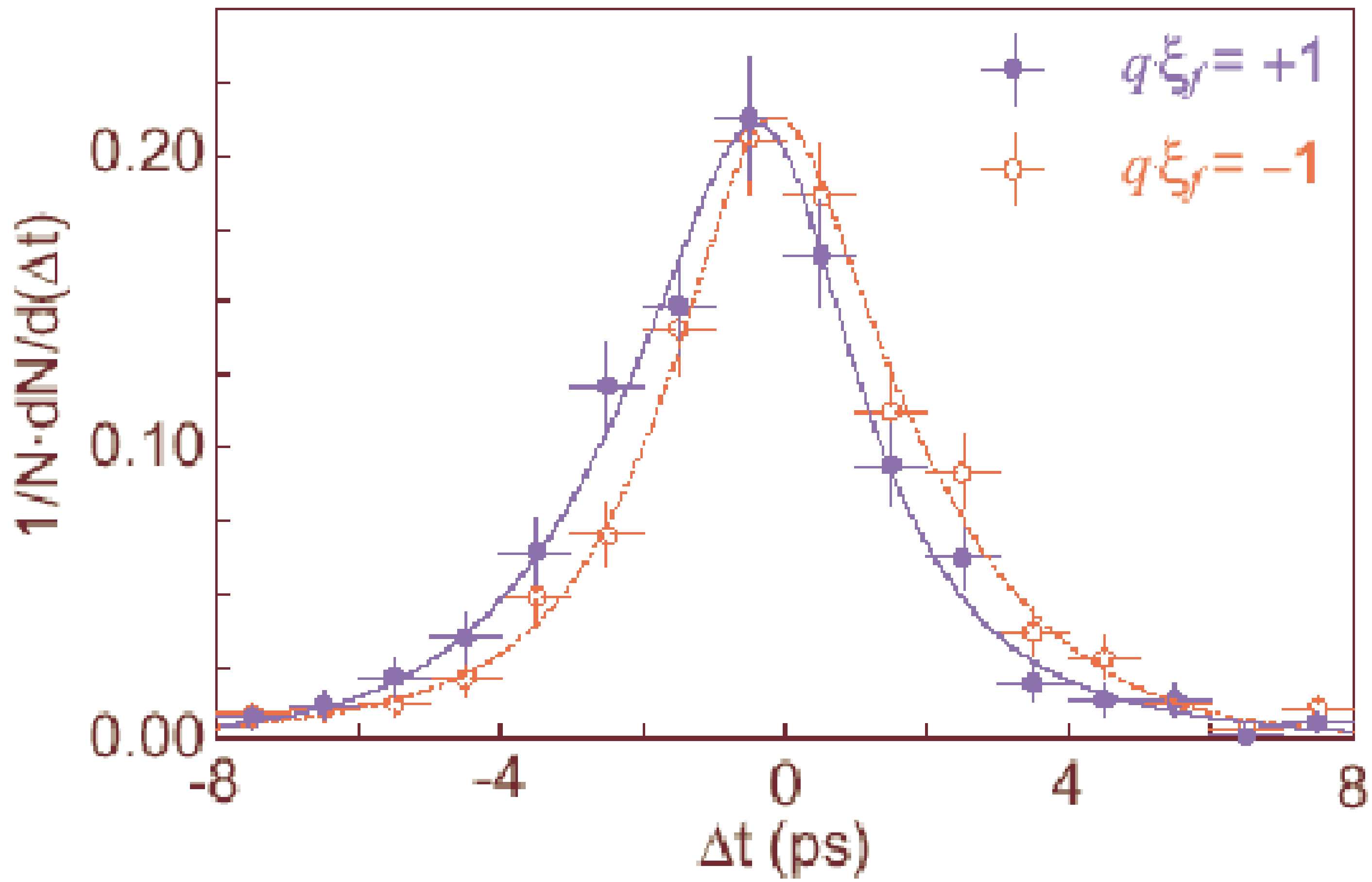
Test of Vertexing – B Lifetime



$$\tau_{B^0} = 1.55 \pm .02 \text{ ps (PDG}: 1.55 \pm .03 \text{ ps)}$$

$$\tau_{B^\pm} = 1.64 \pm .03 \text{ ps (PDG}: 1.65 \pm .03 \text{ ps)}$$

The Combined Fit (All Charmonium States)



Sources of Systematic Error

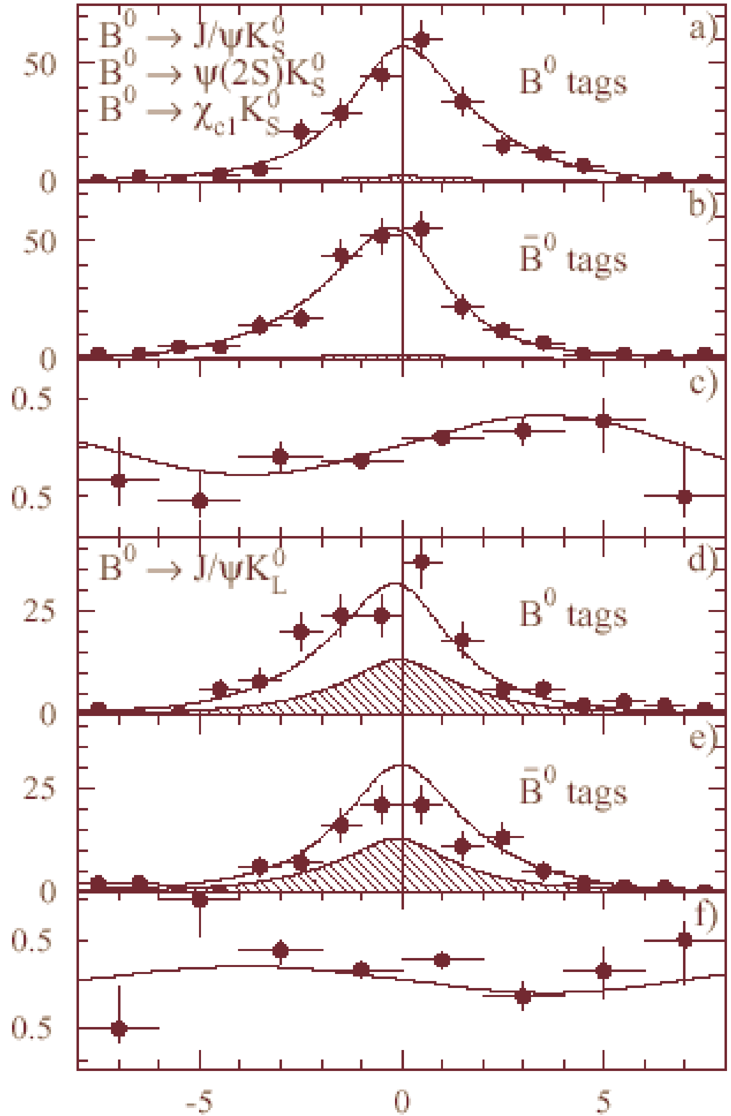
Source	σ
Vertex Algorithm	.04
Flavor Tagging	.03
Resolution Function	.02
K_L Background Fraction	.02
Background Shapes	.01
Δm_d and τ_B Errors	.01
Total	**.06**

- Bottom Line

$$\boxed{\sin 2\phi_1 = .99 \pm .14(stat) \pm .06(syst.)}$$

Published in **Phys.Rev.Lett. 87, 091802 (2001)**

The BaBar Measurement

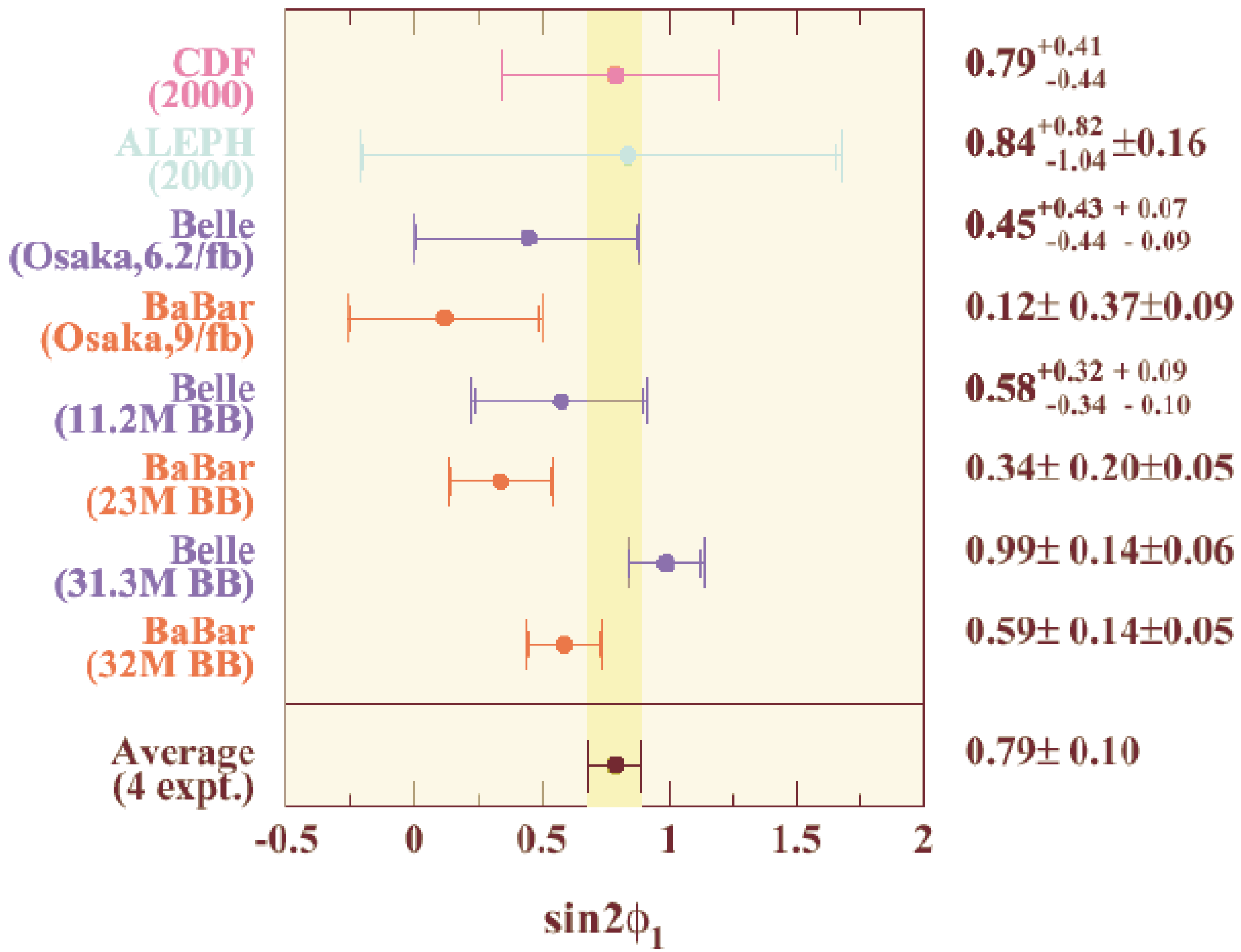


Based on 32 million B-Bbar pairs

$$\boxed{\sin 2\beta = .59 \pm .14 \pm .05}$$

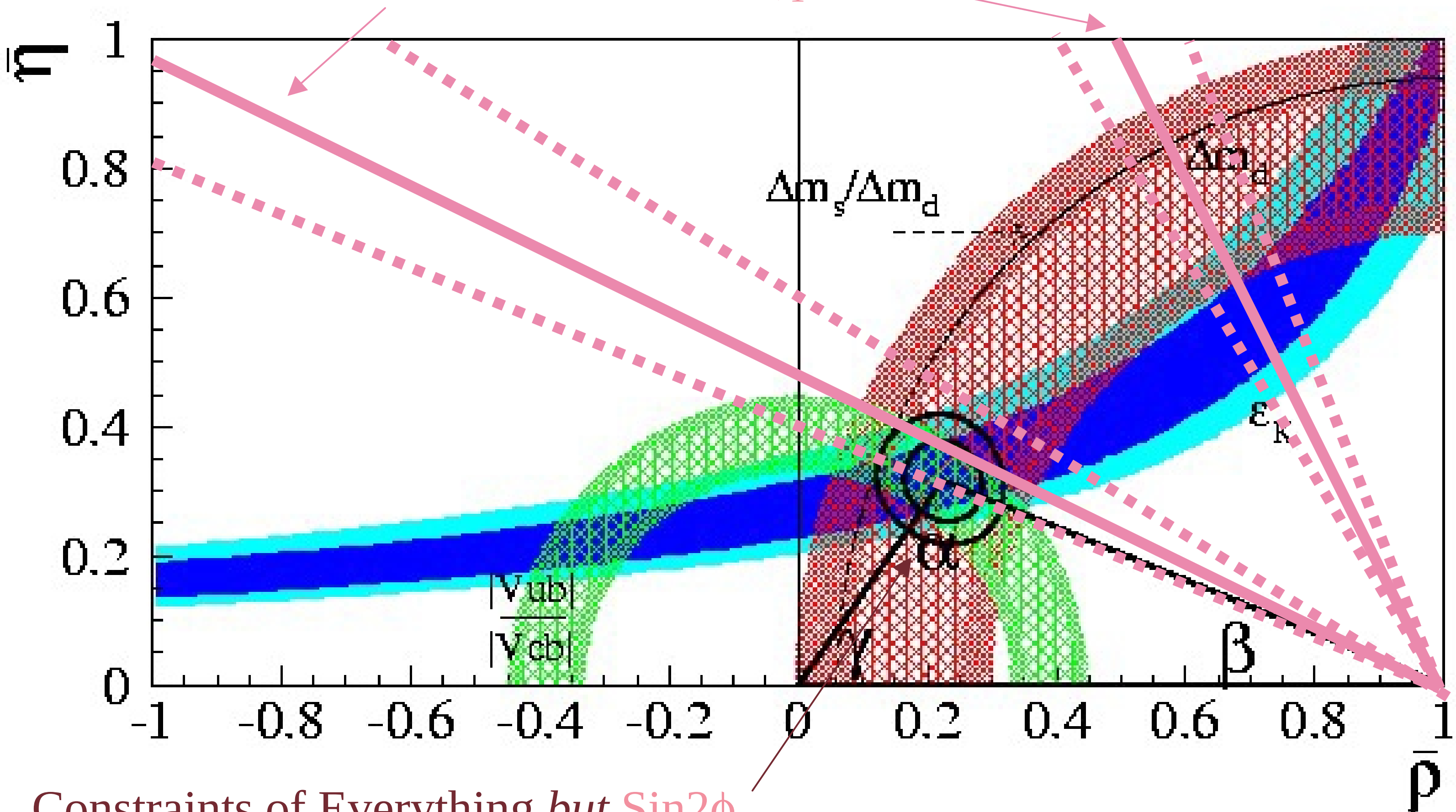
Phys.Rev.Lett. 87 (2001)

Summary of $2\phi_1$ Measurements



How About That $\rho\!-\!\eta$ Plane?

World Average $\sin 2\phi_1$ ($\pm 1\sigma$)



Constraints of Everything *but* $\sin 2\phi_1$

Looks good for the Standard Model, but a little *dull* for experimenters !

Current Status

- The study of CP Violation has been going on for *almost 40 years!*
- A number of experiments are currently taking data which seem to be confirming the Standard Model (CKM) explanation of CP Violation, and thereby constraining that model
  - Direct CP violation is observed in the neutral K system!
  - CP *is* violated in the B-Meson system!
- Over the next several years, the existing B-Factories will continue to take data, providing tighter and tighter constraints.
- New players are also coming on the scene:
  - Fermilab Run II (CDF and D0) - now
  - BTeV (dedicated B Experiment at Fermilab) - ~2005
  - LHC (Atlas and CMS) - 2006
  - LHC-B (dedicated B Experiment at LHC) - ?

More "Out There"

- CP Violation in the ν sector? (probably there, hard to study)
- CPT Violation?
  - CPT Conservation is a direct consequence of the Lorentz invariance of the Lagrangian.
  - Evidence of its violation would be observation (direct or indirect) of

$$m(p) \neq m(\overline{p}) \quad \text{or} \quad \Gamma(p) \neq \Gamma(\overline{p})$$

  and would be big news.

- We still can't answer why the unverse is all matter. Maybe it *isn't*!
  - The AMS experiment, set to fly on the ISS, will look for massive anti-nuclei to test the hypothesis that distant parts of the universe *might* be antimatter (!!)

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).

Differences Between PEP-II (BaBar) and KEKB (Belle)

•PEP-II has complex IR optics to force beams to collide head-on.

Pros: Interaction of head-on beams well understood.

Cons: Complicates IR design.
More synchrotron radiation.
Can't populate every RF bucket.

• In KEK-B, the beams cross at ±11 mr.

Pros: Simple IR design.
Can populate every RF bucket.
Lower (but not zero!!!) synchrotron radiation.

Cons: Crossing can potentially couple longitudinal and transverse instabilities.

At present, both designs seem to be working.

Differences (cont'd)

Readout:

• BaBar uses an SLD-inspired system, based on a continuous digitization. The entire detector is pipelined into a software-based trigger.

Pros: Extremely versatile trigger.
Less worry about hardware-based trigger systematics.
Can go to very high luminosities.

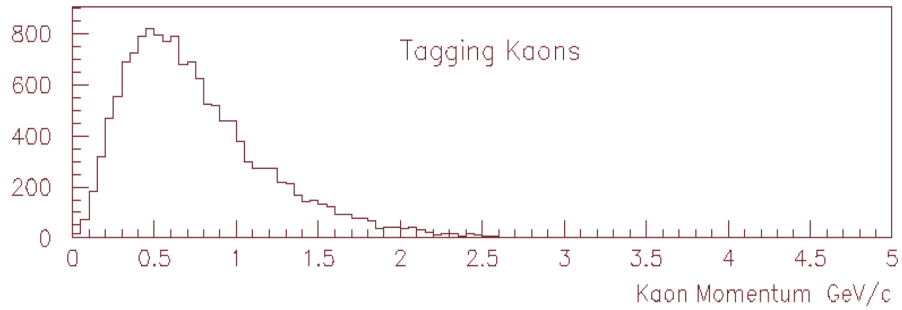
Cons: Required development of lots of custom hardware.

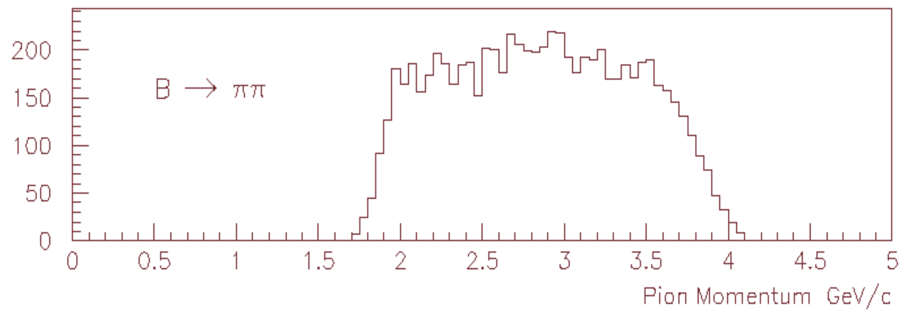
• Belle's readout is based on converting signals to time-pulses. The trigger is an "old-fashioned" hardware-based level one. Events satisfying level one are read out after a 2 μs latency.

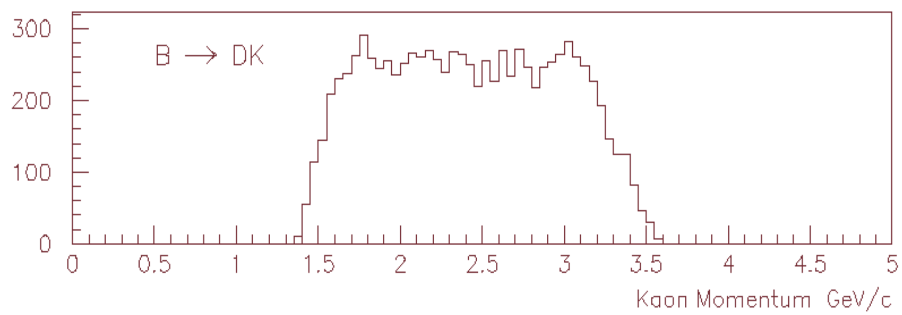
Pros: Simple.
Readout relies largely on "off-the-shelf" electronics.

Cons: Potential for hardware-based trigger systematics.
Possible problems with high luminosity.

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