CP Violation in the B System

An Experimental View

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Outline

1. **Introduction:**
   - Charged Current Decays
   - the CKM Matrix
   - $B/\overline{B}$ Mixing
2. CP **violation**
   - Introduction
   - the $J/\psi K^0_S$ Mode
3. **the Measurement of** $\sin 2\beta$
   - the Fermilab Tevatron
   - the CDF Detector
   - the $J/\psi K^0_S$ Sample
   - Flavor Tagging
   - Results
4. **Outlook: Other** CP **Modes**
5. **Summary**

Cheat Sheet

Fermions (spin 1/2)

generation	I	II	III	charge
Leptons:				
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$	-1 0
	free particles			
Quarks:				
	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$	+2/3 -1/3
	bound states: $q\bar{q}$, qqq			

Mesons:

$$B^0 = |\bar{b}d> \qquad \overline{B^0} = |b\bar{d}>$$
$$B^+ = |\bar{b}u> \qquad B^- = |b\bar{u}>$$
$$B_s^0 = |\bar{b}s> \qquad \overline{B_s^0} = |b\bar{s}>$$
$$K_S^0 = \frac{1}{\sqrt{2}}(|d\bar{s}> + |s\bar{d}>) \qquad \pi^+ = |u\bar{d}>$$
$$K_L^0 = \frac{1}{\sqrt{2}}(|d\bar{s}> - |s\bar{d}>) \qquad \pi^- = |\bar{u}d>$$
$$J/\psi = |c\bar{c}> \qquad \pi^0 = \frac{1}{\sqrt{2}}(|u\bar{u}> + |d\bar{d}>)$$

Weak Decays

Interactions: **The only decay mechanism that changes flavor is the weak interaction.**

- **Strong Interaction:**

  $\rightarrow\ \phi \rightarrow K^+K^-$ **(**$|s\bar{s}> \rightarrow |s\bar{u}> + |\bar{s}u>$**)**

  $\rightarrow$ **conserves flavor**

- **Electromagnetic interaction:**

  $\rightarrow\ \pi^0 \rightarrow \gamma\gamma$ **(**$|u\bar{u}> \rightarrow \gamma\gamma$**)**

  $\rightarrow$ **conserves flavor**

- **Weak neutral current:**

  $\rightarrow\ Z^0 \rightarrow b\bar{b}$

  $\rightarrow$ **conserves flavor**

- **Charged neutral current:**

  $\rightarrow\ B^- \rightarrow D^0\ell\nu$ **(**$b \rightarrow c$**)**

  $\rightarrow$ **does not conserve flavor**

Why are B's so Interesting?

Bottom quark: discovered in 1977. Several thousand papers since then (theory+experiment: production, decay, couplings, mixing, etc.)

Two new accelerators + several new experiments have been built to study B hadrons.

Why is this Beast so interesting?

- **it's heavy:** $m_b \simeq 5m_p$
- **it couples most strongly to the ultramassive top quark (**$m_t \simeq 175m_p$**)**

  $\rightarrow$ **but it can't decay to top!**
- **it has a long lifetime** $\tau_b = 1.5\,\mathrm{psec}$ **(**$c\tau_b = 450\,\mu\mathrm{m}$**)**
- **it has a long** $B^0/\bar{B}^0$ **mixing frequency**

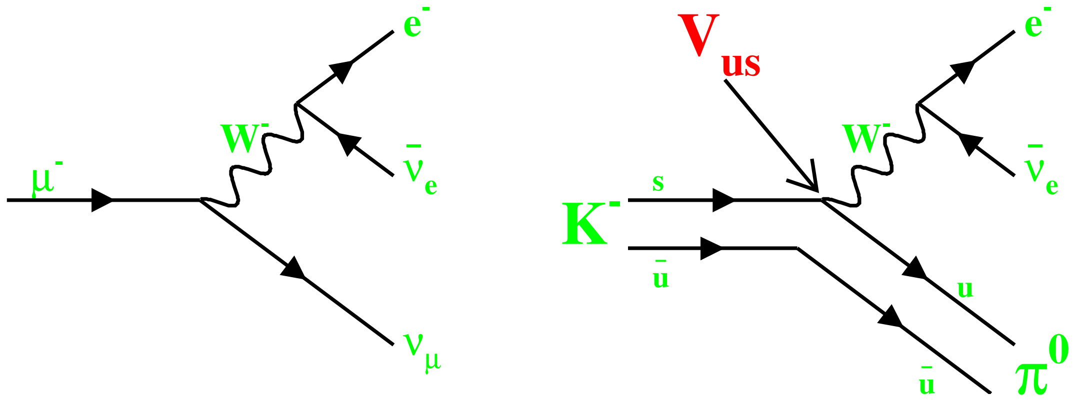
  $\rightarrow$ **fully mixes in about 4.4 lifetimes**
- **expected to show LARGE** CP **violating effects**

  $\rightarrow$ **LARGE**$\simeq 10 - 30\%$

  $\rightarrow$ CP **violation in the kaon system:** 0.1%

The Cabibbo-Kobayashi-Maskawa Matrix

Weak charged-current decay ($W^{\pm}$ exchange):



$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{\dagger}_{\mu} + h.c.,$$

where

$$J^{\mu}_{cc} = (\overline{\nu_e}, \overline{\nu_\mu}, \overline{\nu_\tau})\gamma^{\mu} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^{\mu} V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

and

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

is the Cabibbo-Kobayashi-Maskawa (CKM) Mixing Matrix which rotates quark mass eigenstates into weak eigenstates.

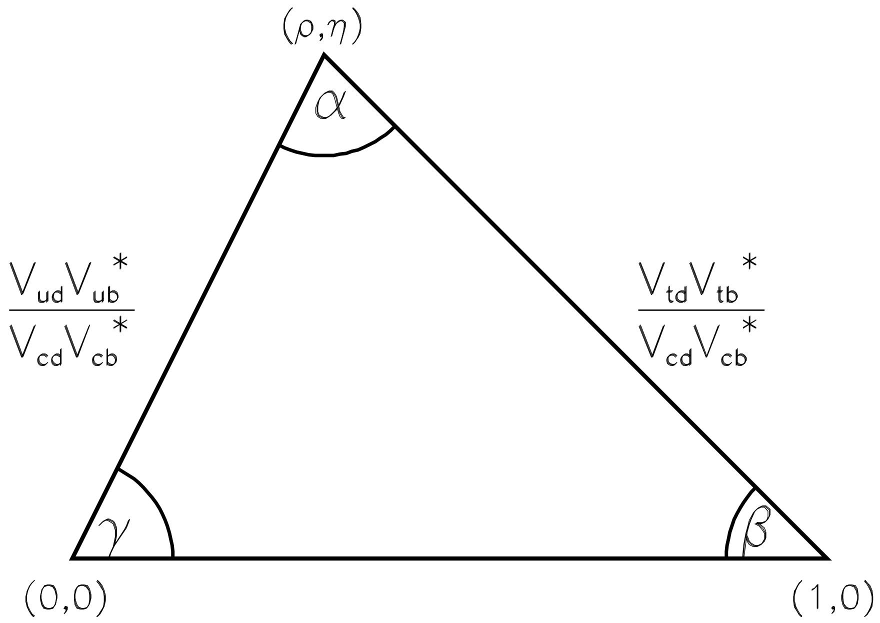
The Cabibbo-Kobayashi-Maskawa Matrix

The Wolfenstein parameterization:

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

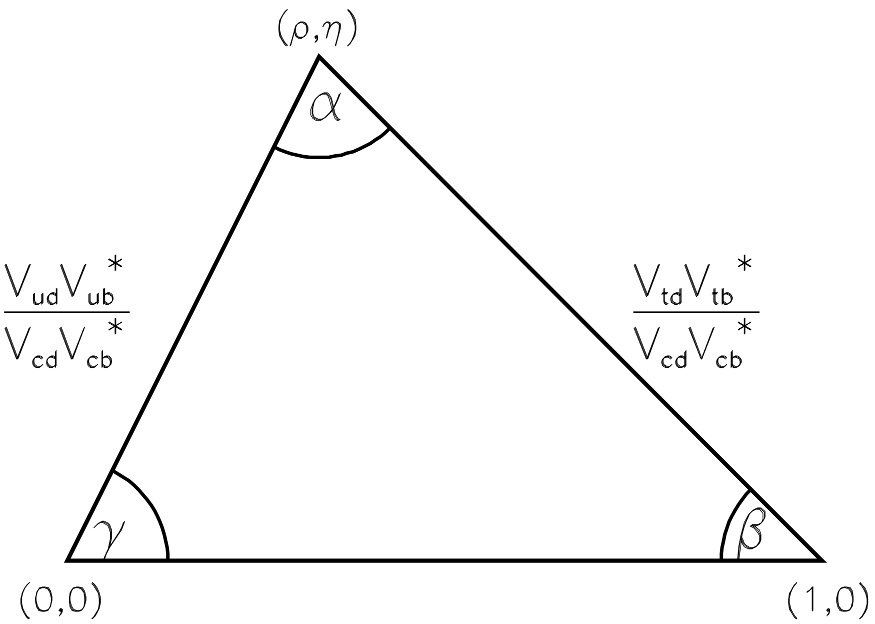
- $\lambda = \sin\theta_C$, **sine of the Cabibbo angle,** $\lambda = 0.22$
  - $\Gamma(K \to \pi) \sim |V_{us}|^2 \simeq \sin^2\theta_C = \lambda^2$
- **unitarity** $\Rightarrow V^\dagger V = 1$

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



The unitarity triangle

The Unitary Triangle



Goal of current and future experiments is to measure both sides and three angles in as many ways possible: overconstrain the triangle to look for new physics.

Examples:

- B_d **and** B_s^0 **mixing are** $\Rightarrow\ |V_{td}/V_{ts}|$
- $b \to u$ **decays** $\Rightarrow\ |V_{ub}|$
- CP **violation in** $J/\psi K_S^0 \Rightarrow\ \beta$
- CP **violation in** $B^0 \to \pi^+\pi^- \Rightarrow\ \alpha$
- CP **violation in** $B_s^0 \to D_s K \Rightarrow\ \gamma$

Unitarity Relations

Unitary Cabibbo-Kobayashi-Maskawa (CKM) Mixing Matrix:

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

Unitarity $\Rightarrow V^\dagger V = VV^\dagger = 1$

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

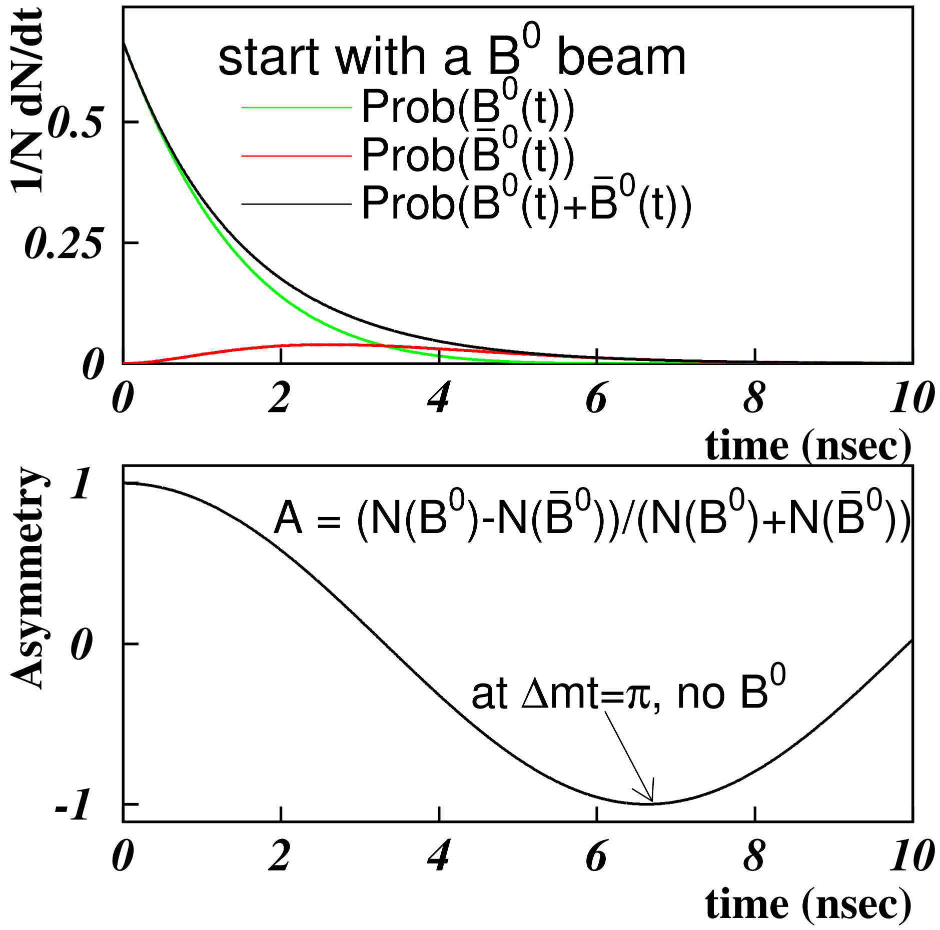
This relation is quite useful because each term is of order λ^3.

$B^0/\overline{B^0}$ Mixing

For initial state $= B^0$:

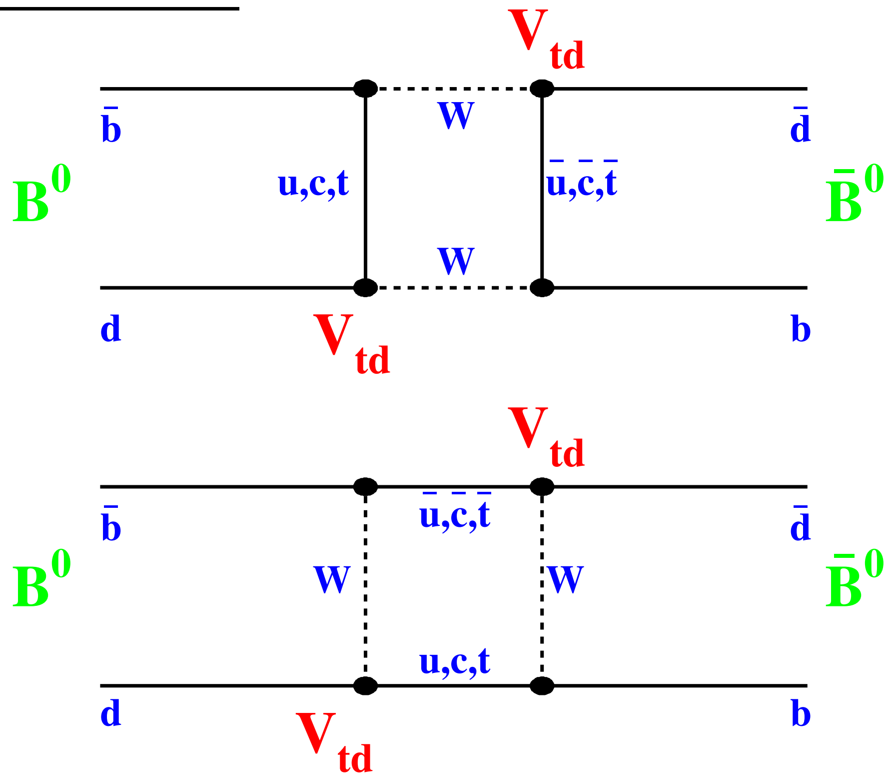
$$P(B^0(t)) = \frac{1}{2\tau}e^{-\frac{t}{\tau}}(1+\cos(\Delta m_d t))$$

$$P(\overline{B^0}(t)) = \frac{1}{2\tau}e^{-\frac{t}{\tau}}(1-\cos(\Delta m_d t))$$



- **weak eigenstates $\neq$ strong eigenstates**
- **Δm_d: mass difference between the heavy and light weak eigenstates ($\Delta m_d = 0 \Rightarrow$ no mixing)**

$B^0/\overline{B^0}$ Mixing



$$B^0, \overline{B^0} : \text{Flavor Eigenstates}$$

$$B^0_H, B^0_L : \text{Mass Eigenstates}$$

$$\Delta m_d = m_H - m_L$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L \; (\simeq 0)$$

For initial state $= B^0$**:**

$$P(B^0(t)) = \frac{1}{2}\Gamma e^{-\Gamma t}(\cosh(\frac{1}{2}\Delta\Gamma t) + \cos(\Delta m_d t))$$

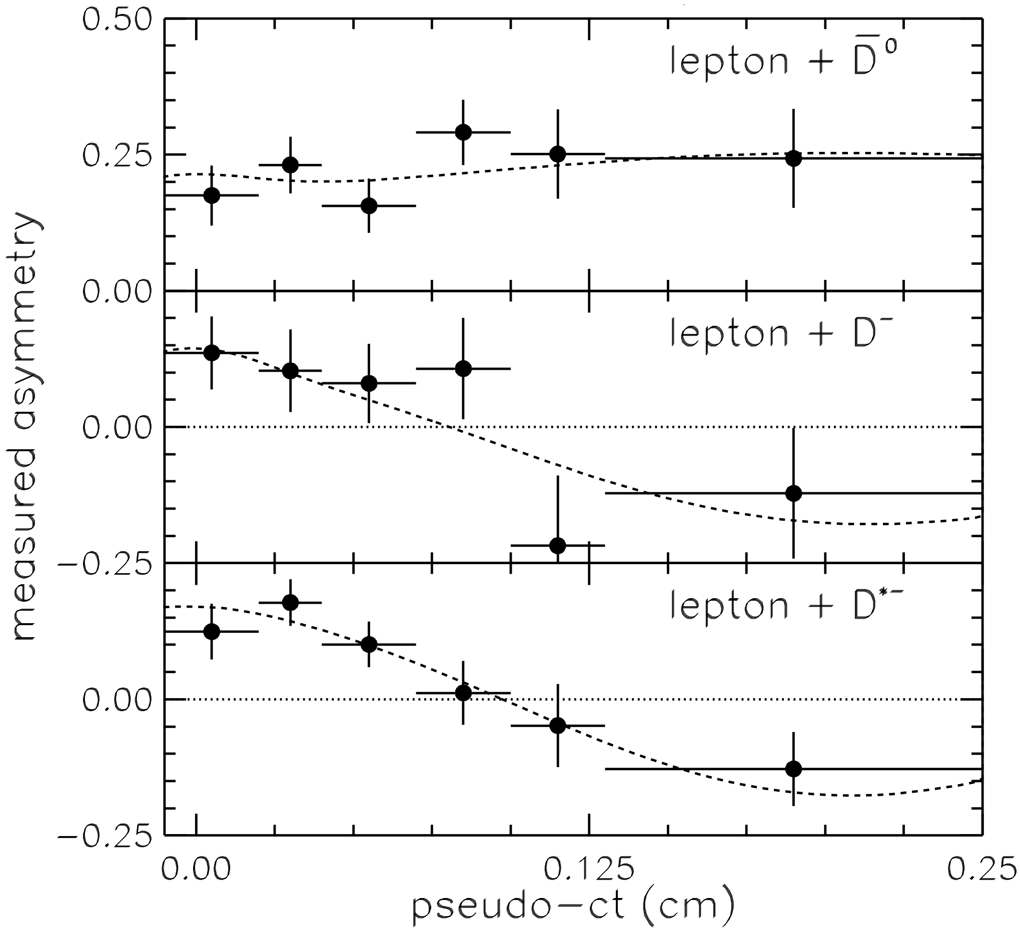
$$P(B^0(t)) \simeq \frac{1}{2}\Gamma e^{-\Gamma t}(\quad 1 \quad + \cos(\Delta m_d t))$$

B^0 **fully mixes to** $\overline{B^0}$ **after** $\Delta mt = \pi \simeq 4.4$ **lifetimes**

Example Mixing Measurement

Ph.D. thesis of P. Maksimović

PRL 80, 2057 (1998).



$B^+ \to \ell^+ D^0$
3000 ev

$B^0 \to \ell^+ D^-$
2000 ev

$B^0 \to \ell^+ D^{*-}$
4300 ev

- **top plot: charged $B^\pm$ do not mix!**
- **middle/bottom plots:**
  - $\mathcal{A} = \frac{N_{unmixed} - N_{mixed}}{N_{unmixed} + N_{mixed}}$
    - $\mathcal{A} = 1 \Rightarrow$ **all unmixed**
    - $\mathcal{A} = -1 \Rightarrow$ **all mixed**
    - $|\mathcal{A}|_{max} < 1$ **due to experimental effects**

Symmetries

1. **parity inversion:** P *look in the mirror*
   - $P\psi(\vec{r}) \to \psi(-\vec{r})$
   - **left-handed** $\Rightarrow$ **right-handed**
   - $P|e_L^- > \to |e_R^- >$
2. **charge conjugation:** C *particle* $\to$ *antiparticle*
   - **particle** $\to$ **antiparticle**
   - $C|p > \to |\overline{p} >$
3. **time reversal:** T *run the film backwards*
   - $T\psi(t) \to \psi^*(-t)$

Symmeties are "preserved" if the operator commutes with the Hamiltonian.

e.g. **the electromagnetic interaction conserves all three of the above symmetries:**

$$[H_{em}, P] = [H_{em}, C] = [H_{em}, T] = 0$$

CP Violation

If CP is a valid symmetry, then an interaction for a

left-handed particle

must be the same as an interaction for a

right-handed antiparticle

$$\begin{array}{cc} \uparrow & \uparrow \\ P & C \end{array}$$

If CP is violated, then some force of nature must be able to tell the difference between a

left-handed quark

and

right-handed antiquark

Note: CP violation is one of the conditions necessary for the universal matter asymmetry... some process must create (and destroy) quarks and antiquarks at unequal rates!!!

CP Violation

Since 1964, CP violation has still only been seen in the neutral kaon system.

The standard model predicts that we should see it in the neutral B system as well:

- $B^0 = |\bar{b}d>$
- $\overline{B^0} = |b\bar{d}>$

Now, we will discuss a search for CP violation in the neutral B system. The type of CP violation we are looking for is of the form:

$$\frac{dN}{dt}(B^0 \to J/\psi K^0_S) \neq \frac{dN}{dt}(\overline{B^0} \to J/\psi K^0_S)$$

where

- $J/\psi = |c\bar{c}>$ $\qquad J/\psi \to \mu^+\mu^-$
- $K^0_S = \frac{1}{\sqrt{2}}(|d\bar{s}> + |s\bar{d}>)$ $\qquad K^0_S \to \pi^+\pi^-$

and $J/\psi K^0_S$ is a CP eigenstate:

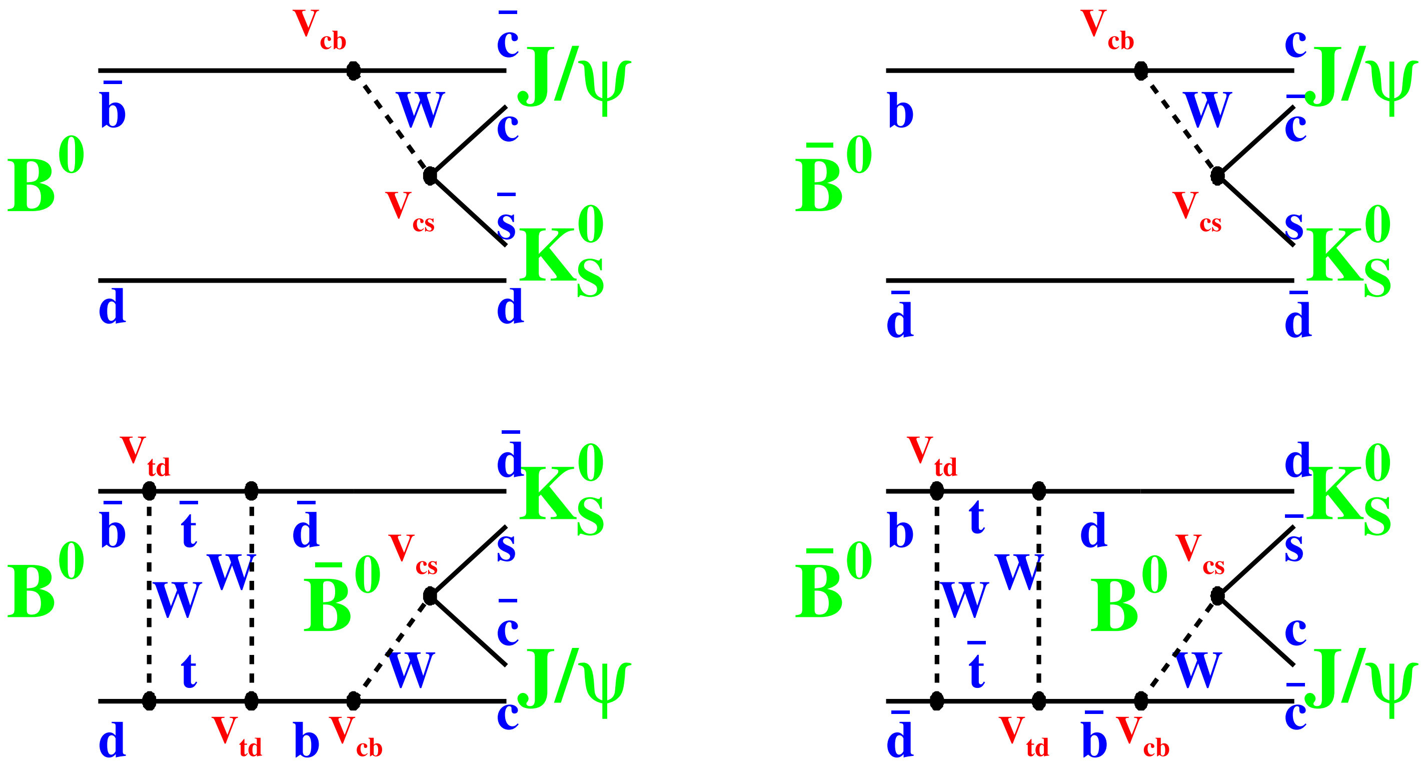
$$CP|J/\psi K^0_S >= -|J/\psi K^0_S >$$

“Mixing Induced” CP Violation

Two paths to the same final state:

- **direct decay ($B^0 \to J/\psi K^0_S$)**
- **mixed decay ($B^0 \to \overline{B^0} \to J/\psi K^0_S$)**

The mixed decay accumulates a phase relative to the direct decay.

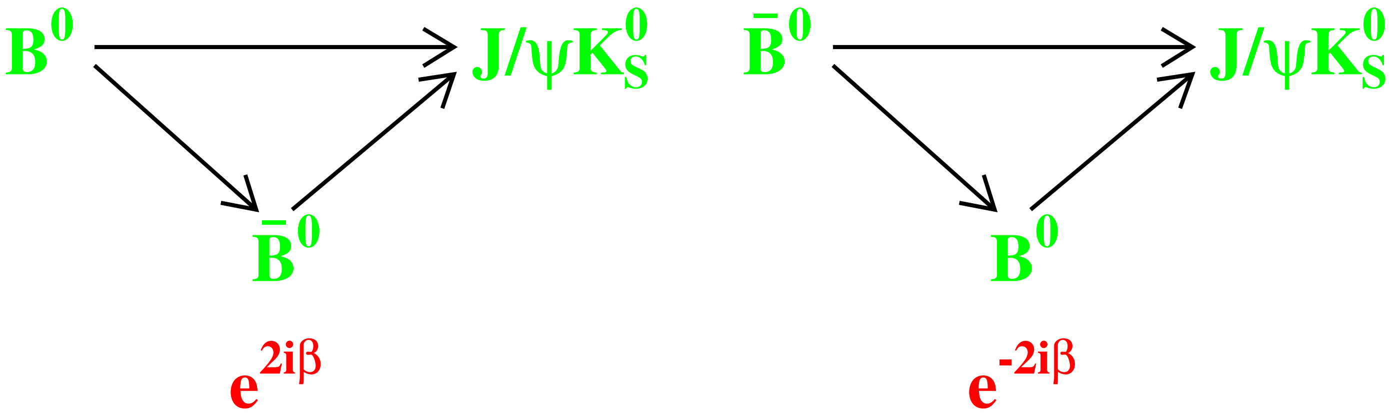


↑ **produce B^0 at $t = 0$**

↑ **produce $\overline{B^0}$ at $t = 0$**

"Mixing Induced" CP Violation

The "direct" decay interferes with the mixed decay.



For $B \to J/\psi K_S^0$ the phase 2β arises from the interference.

produce $\overline{B^0}$ at $t = 0$:

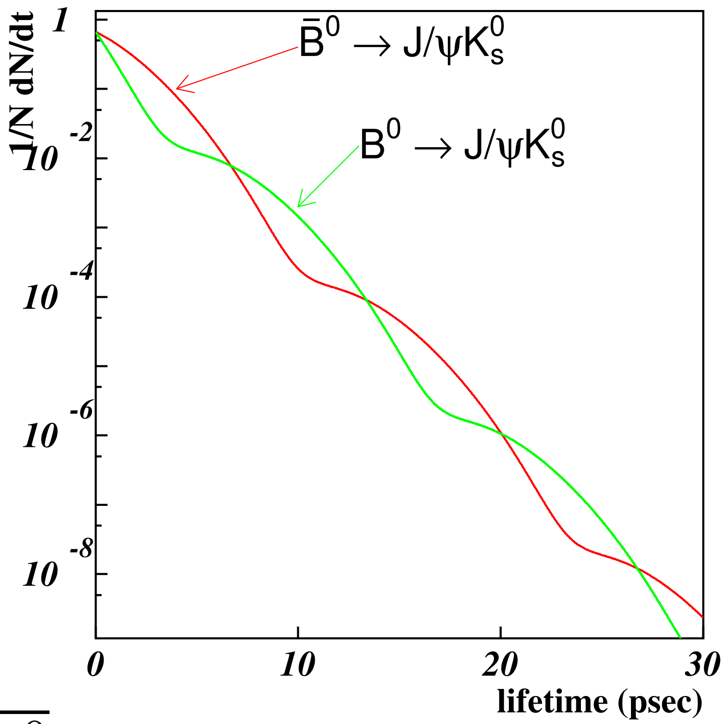
$$\frac{dN}{dt}(\overline{B^0} \to J/\psi K_s^0) \propto e^{-t/\tau}(1 + \sin 2\beta \sin \Delta m t)$$

produce B^0 at $t = 0$:

$$\frac{dN}{dt}(B^0 \to J/\psi K_s^0) \propto e^{-t/\tau}(1 - \sin 2\beta \sin \Delta m t)$$

CP Violation

The interference causes $dN/dt \neq e^{-t/\tau}$



produce $\overline{B^0}$ **at** $t = 0$**:**

$$\frac{dN}{dt}(\overline{B^0} \rightarrow J/\psi K_s^0) \propto e^{-t/\tau}(1 + \sin 2\beta \sin \Delta m t)$$

produce B^0 **at** $t = 0$**:**

$$\frac{dN}{dt}(B^0 \rightarrow J/\psi K_s^0) \propto e^{-t/\tau}(1 - \sin 2\beta \sin \Delta m t)$$

$$A_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B^0} \rightarrow J/\psi K_S^0) - \frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0)}{\frac{dN}{dt}(\overline{B^0} \rightarrow J/\psi K_S^0) + \frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0)}$$

CP Violation

$$A_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B^0} \to J/\psi K^0_S) - \frac{dN}{dt}(B^0 \to J/\psi K^0_S)}{\frac{dN}{dt}(\overline{B^0} \to J/\psi K^0_S) + \frac{dN}{dt}(B^0 \to J/\psi K^0_S)}$$

$$A_{CP}(t) = \sin 2\beta \ \sin(\Delta m_d t)$$

$$\uparrow \qquad\qquad \uparrow$$

amplitude **mixing**

Goal: to measure $\sin 2\beta$.

(Note:Δm_d well-measured.)

(Standard Model expectation: $\sin 2\beta \simeq 0.75$.)

If $\sin 2\beta = 0$, no CP violation, the Standard Model is wrong!

If $\sin 2\beta \neq 0$, observe CP violation in the B system for the first time.

Time Integrated $\sin 2\beta$

$$A_{CP} = \frac{\frac{dN}{dt}(\overline{B}^0 \to \psi K^0_S) - \frac{dN}{dt}(B^0 \to \psi K^0_S)}{\frac{dN}{dt}(\overline{B}^0 \to \psi K^0_S) + \frac{dN}{dt}(B^0 \to \psi K^0_S)}$$

- $A_{CP}(t) = \sin 2\beta \times \sin(\Delta m t)$

time integrated:

$$\begin{aligned}
A_{CP} &= \frac{\int \frac{dN}{dt}(\overline{B}^0 \to \psi K^0_S)dt - \int \frac{dN}{dt}(B^0 \to \psi K^0_S)dt}{\int \frac{dN}{dt}(\overline{B}^0 \to \psi K^0_S)dt + \int \frac{dN}{dt}(B^0 \to \psi K^0_S)dt} \\
A_{CP} &= \frac{N(\overline{B}^0 \to \psi K^0_S) - N(B^0 \to \psi K^0_S)}{N(\overline{B}^0 \to \psi K^0_S) + N(B^0 \to \psi K^0_S)} \\
A_{CP} &= \frac{\Delta m_d \tau_B}{1 + (\Delta m_d \tau_B)^2} \cdot \sin 2\beta \\
A_{CP} &\simeq 0.47 \sin 2\beta
\end{aligned}$$

Note: only valid for incoherent $b\overline{b}$ production (true at hadron colliders.)

Assumptions

$$A_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B^0} \to J/\psi K_S^0) - \frac{dN}{dt}(B^0 \to J/\psi K_S^0)}{\frac{dN}{dt}(\overline{B^0} \to J/\psi K_S^0) + \frac{dN}{dt}(B^0 \to J/\psi K_S^0)}$$

$$A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$$

We assume the following things to be true in this analsysis: (all assumptions are quite good)

- $\Delta\Gamma = \Gamma_H - \Gamma_L \simeq 0$
- $B^0 \to J/\psi K_S^0$ **via penguin is small**

  $\to$ $g \to c\overline{c}$ **is mass-suppressed**

  $\to$ **if present, complicates** $A_{CP}(t)$ **with** $\cos(\Delta m t)$ **term**
- K_S^0 **is** 100% CP **even**
- $N(B^0) = N(\overline{B^0})$ **at** $t = 0$

  $\to$ $p\overline{p} \to b\overline{b}X$

  $\to$ **strong interaction preserves bottomness**

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    - **the CKM Matrix**
    - $B/\overline{B}$ **Mixing**
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    - **Introduction**
    - **the** $J/\psi K_S^0$ **Mode**
3. **the Measurement of** $\sin 2\beta$
    - **the Fermilab Tevatron**
    - **the CDF Detector**
    - **the** $J/\psi K_S^0$ **Sample**
    - **Flavor Tagging**
    - **Results**
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5. **Summary**

Analysis Overview

Steps to measure $\sin 2\beta$:

- **sample of $B \to J/\psi K^0_S$ decays**

  $\to$ **lifetime information helps, but not required**

- **need to determine the flavor of the $B^0/\overline{B^0}$ at the time of production**

  $\to$ **this is the limiting factor, so we need to use as many handles as possible**

- **need to handle potential charge biases in the detector**

- **use a maximum likelihood fit to weight events:**

  $\to$ **combines many handles to differentiate signal from background**

  $\to$ **accounts for our multiple methods to discriminate B^0 from $\overline{B^0}$**

The Fermilab Tevatron

- **$p\overline{p}$ collisions**
  - $\rightarrow$ **center of mass energy = $1.8\,\mathrm{TeV}$**
  - $\rightarrow$ **the highest energy collider in the world**
- **data shown here is from the 1992-1996 period**

The high energy of the Tevatron allows us to study the most massive particles known:

W boson, Z boson, t quark

but it also yields (incredibly) copious production of "lighter" particles, like b quarks, which ONLY weigh 5 times more than a proton!

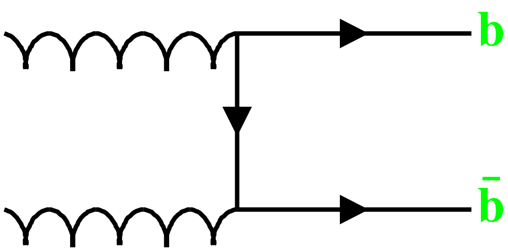
The Tevatron produces 10^{10} $b\overline{b}$ pairs in a year.

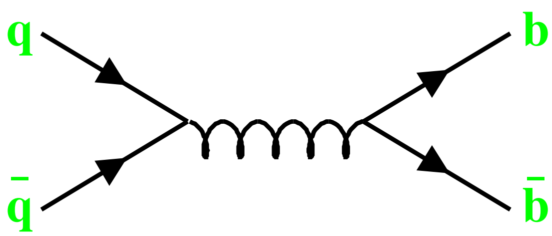
B Physics at the Tevatron

Strong interaction produces b quarks:

$$p\overline{p} \rightarrow b\overline{b} + X$$

e.g.





"gluon fusion"

"$q\overline{q}$ annihilation"

Quarks fragment into hadrons:

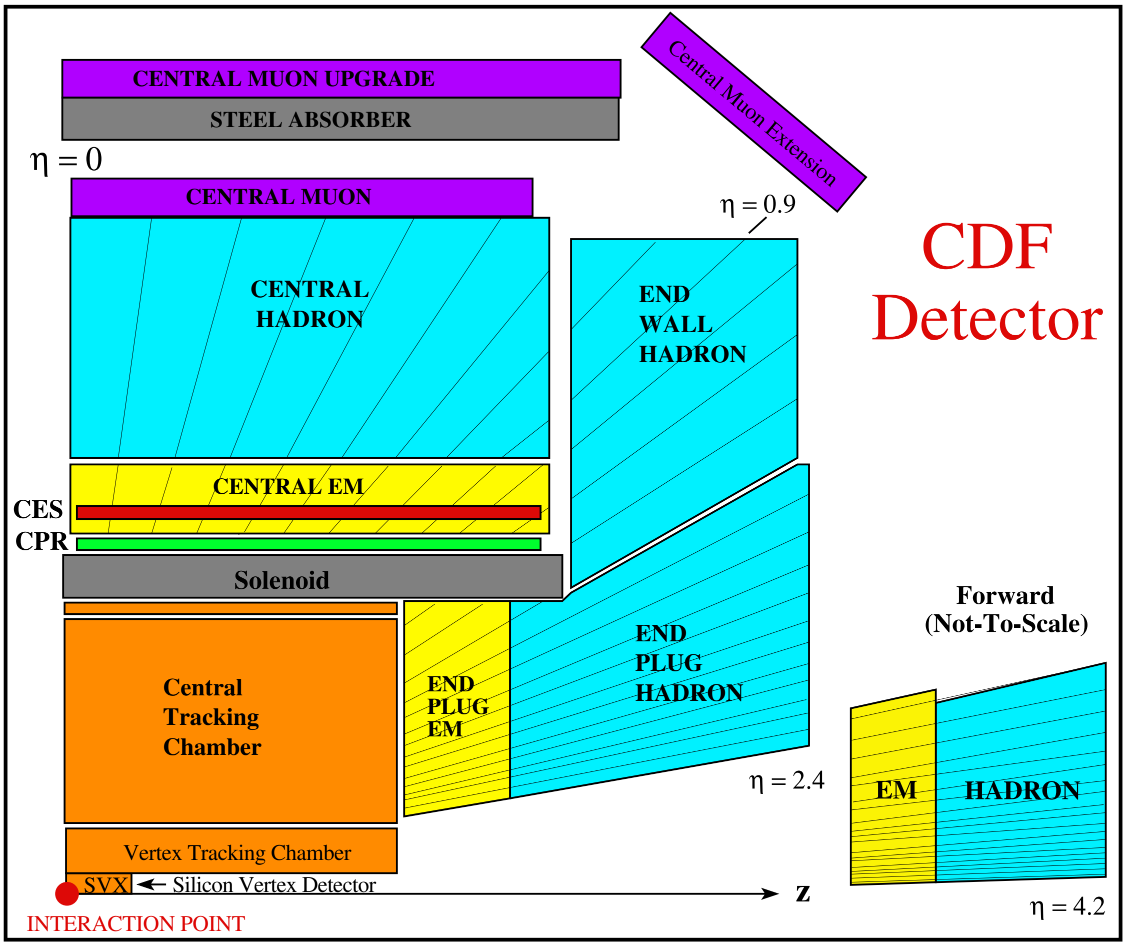
$$\overline{B^0} = b\overline{d}, \ \overline{B_s^0} = b\overline{s}, \ B^- = b\overline{u}, \ \Lambda_b = bdu$$

and then decay via weak interaction:

$$B^+ \rightarrow \overline{D^0}\mu^+\nu_\mu \ (\overline{b} \rightarrow \overline{c}\mu\nu)$$
$$B^0 \rightarrow J/\psi K_S^0 \ (\overline{b} \rightarrow \overline{c}c\overline{s})$$

CP violation arises via the weak interaction $\Rightarrow$ decay mechanism

The CDF Detector



- **Important aspects:**
  - **Silicon vertex detector (SVX)**
    typical 2D vertex error: $60\ \mu\mathrm{m}$
    ($c\tau_B = 450\ \mu\mathrm{m}$**)**
  - **Central tracking chamber (CTC)**
    typical $J/\psi K^0_S$ **mass resolution:**
    $\sim 10\ \mathrm{MeV}/\mathrm{c}^2$
  - **Muon systems, calorimeter**
    crucial for triggering and lepton identification

Triggering

$p\bar{p}$ **crossing rate** $286\,\mathrm{kHz} \Rightarrow$ **crossing every** $3.5\,\mu\mathrm{s}$ **(**2 **interactions/crossing on average)**

We can write events to tape at a rate of $5\,\mathrm{Hz}$

Triggering is CRUCIAL to this experiment.

3 level trigger:

- **Level 1**
  - $\rightarrow$ **look for calorimeter energy and muon stubs**
  - $\rightarrow$ **operates on every crossing**
  - $\rightarrow$ $286\,\mathrm{kHz}$ **in;** $2\,\mathrm{kHz}$ **out**
- **Level 2**
  - $\rightarrow$ **calorimeter clustering, tracking available**
  - $\rightarrow$ **find jets, match tracks to muons, match tracks to clusters (**e**),** $\not\!\!E_T$
  - $\rightarrow$ **decision in** ~ 10**-**$15\,\mu\mathrm{s}$
  - $\rightarrow$ $2\,\mathrm{kHz}$ **in;** $20\,\mathrm{Hz}$ **out**
- **Level 3**
  - $\rightarrow$ **full event read out** $\Rightarrow$ **processor farm**
  - $\rightarrow$ **run a fast version of offline reconstruction**
  - $\rightarrow$ $20\,\mathrm{Hz}$ **in;** $3\,\mathrm{Hz}$ **out to mass storage**

Data Sample

The data shown today were accumulated in the 1992-1996 run of the Tevatron.

- **Roughly 6×10^{12} $p\overline{p}$ interactions.**
- **About $100\,\mathrm{million}$ events written to tape.**
  (roughly 20 Terabytes of data)

In the period 2001-2003, we anticipate accumulating about 50 times as much data.

- **about 1 Petabyte of data**

$B \to J/\psi K_S^0$ Event Selection

- **look for $J/\psi \to \mu^+\mu^-$**

  $\to$ **μ = central track + muon chamber track**

- **look for $K_S^0 \to \pi^+\pi^-$**

  $\to$ **take advantage of long lifetime to reject background: require $L_{xy}/\sigma_{L_{xy}} > 5$**

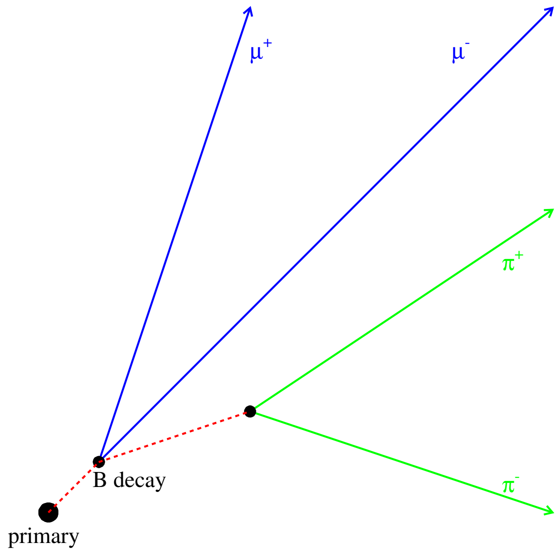
- **perform 4-track fit assuming $B \to J/\psi K_S^0$:**

  – **$\pi^+\pi^-$ constrained to PDG K_S^0 mass**

  – **K_S^0 "points" to B (J/ψ) vertex**

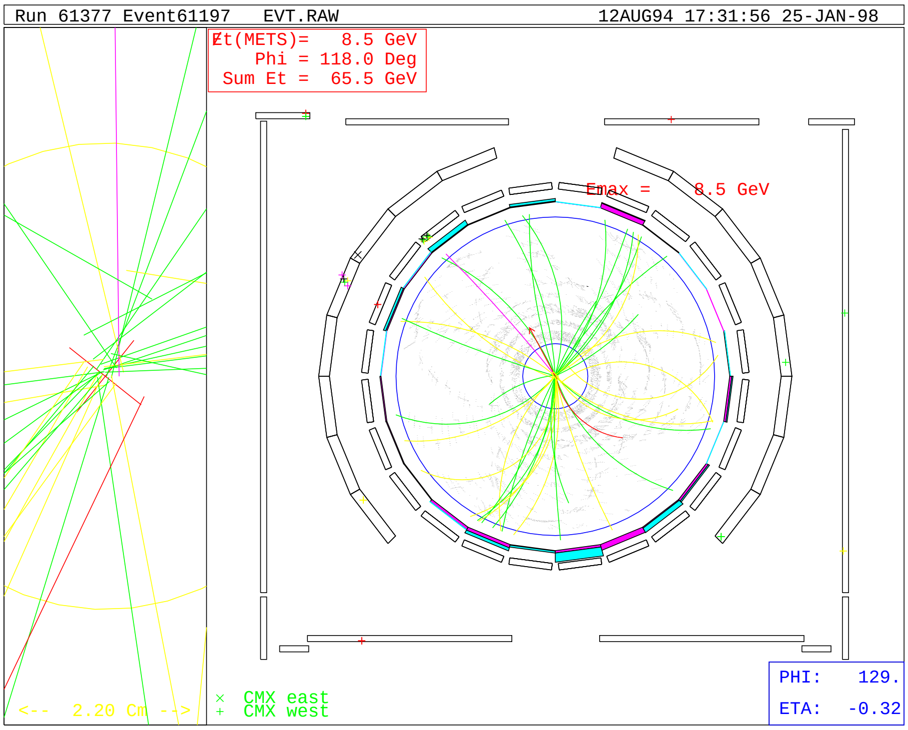
  – **$\mu^+\mu^-$ constrained to PDG J/ψ mass**

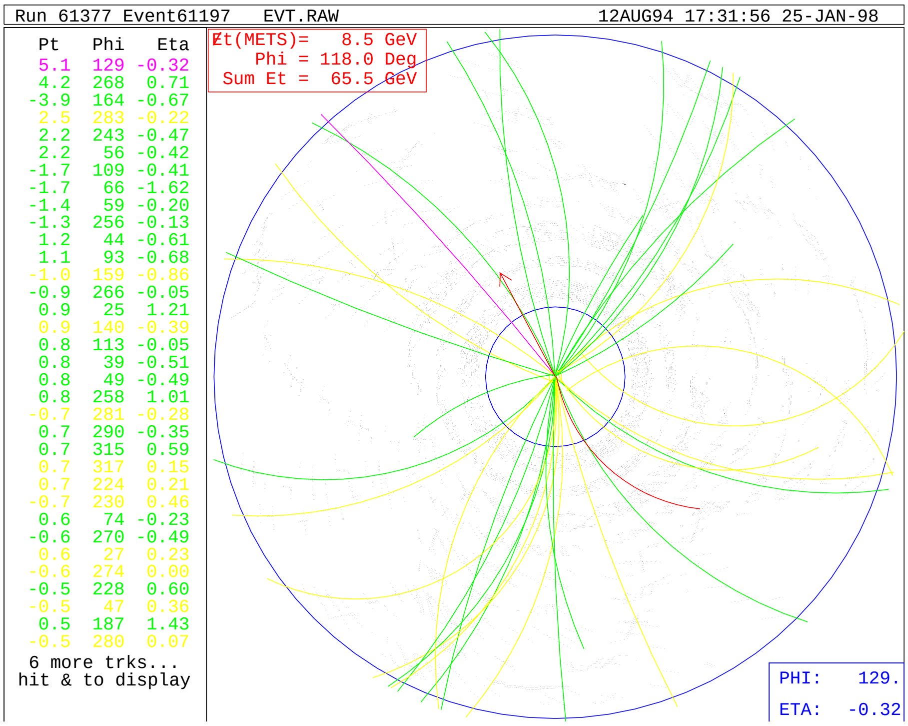
  – **B candidate "points" back to primary vertex**



- **"quality" of fit is used to reject background**

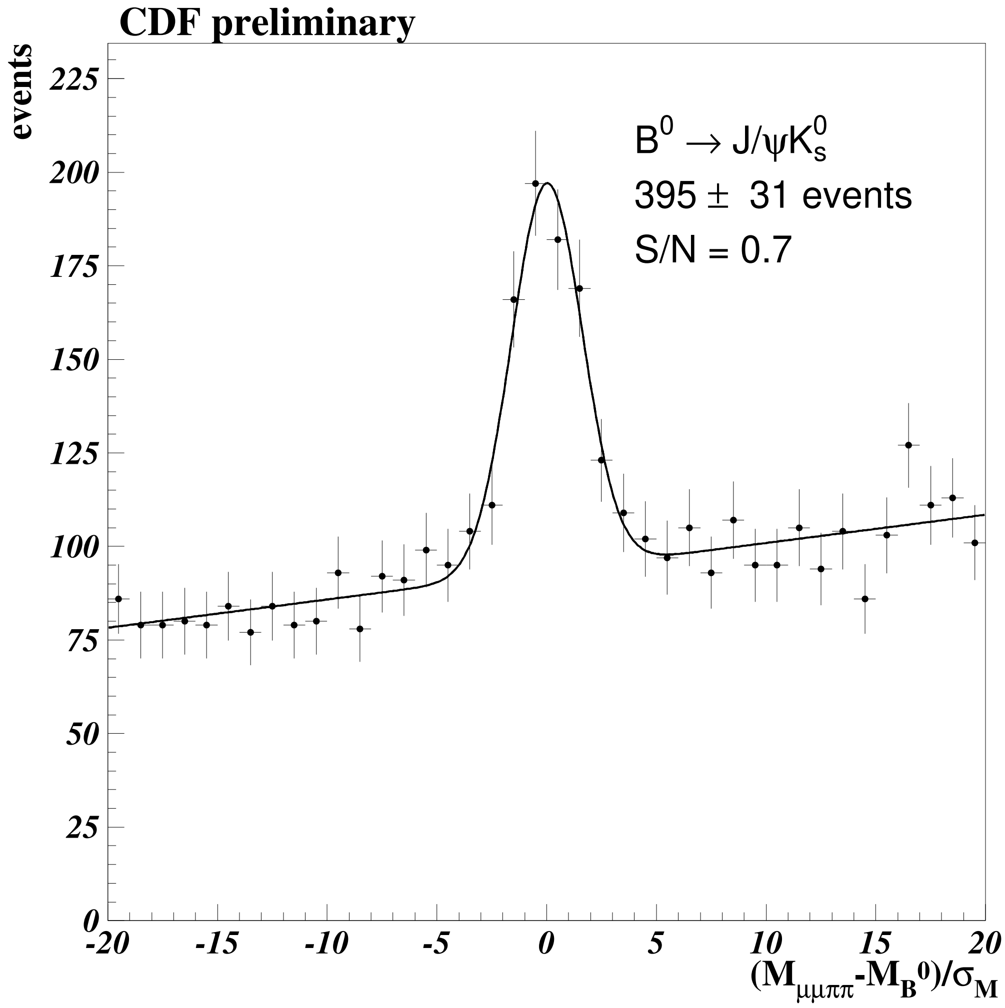
$B \to J/\psi K^*$ Candidate Event





Event Yield

CDF Run I, $\mathcal{L} = 110\,\mathrm{pb}^{-1}$:



- 395 ± 31 **events**
- **"normalized" mass is:** $m_{norm} = \frac{m_{\mu\mu\pi\pi} - m_{B^0}}{\sigma_m}$

  $m_{\mu\mu\pi\pi}$ **is the mass from the four track fit**

  σ_m **the experimental error on that fitted mass.**

  $m_{B^0} = 5.2792\,\mathrm{GeV}/\mathrm{c}^2$ **(world average)**

Where Did All of the Events Go?

During our data taking, the Tevatron produced about 10^{10} $b\bar{b}$ pairs.

We were able to reconstruct about 400 events in this decay mode. Why?

probability that:

b becomes B^0	35%
$B^0 \rightarrow J/\psi K^0_S$	0.04%
$J/\psi \rightarrow \mu^+\mu^-$	6%
$K^0_S \rightarrow \pi^+\pi^-$	67%
tracks are in the detector acceptance	0.4%
total "efficiency"	$\mathbf{2 \times 10^{-8}}$

Yield = events $\times$ "efficiency"

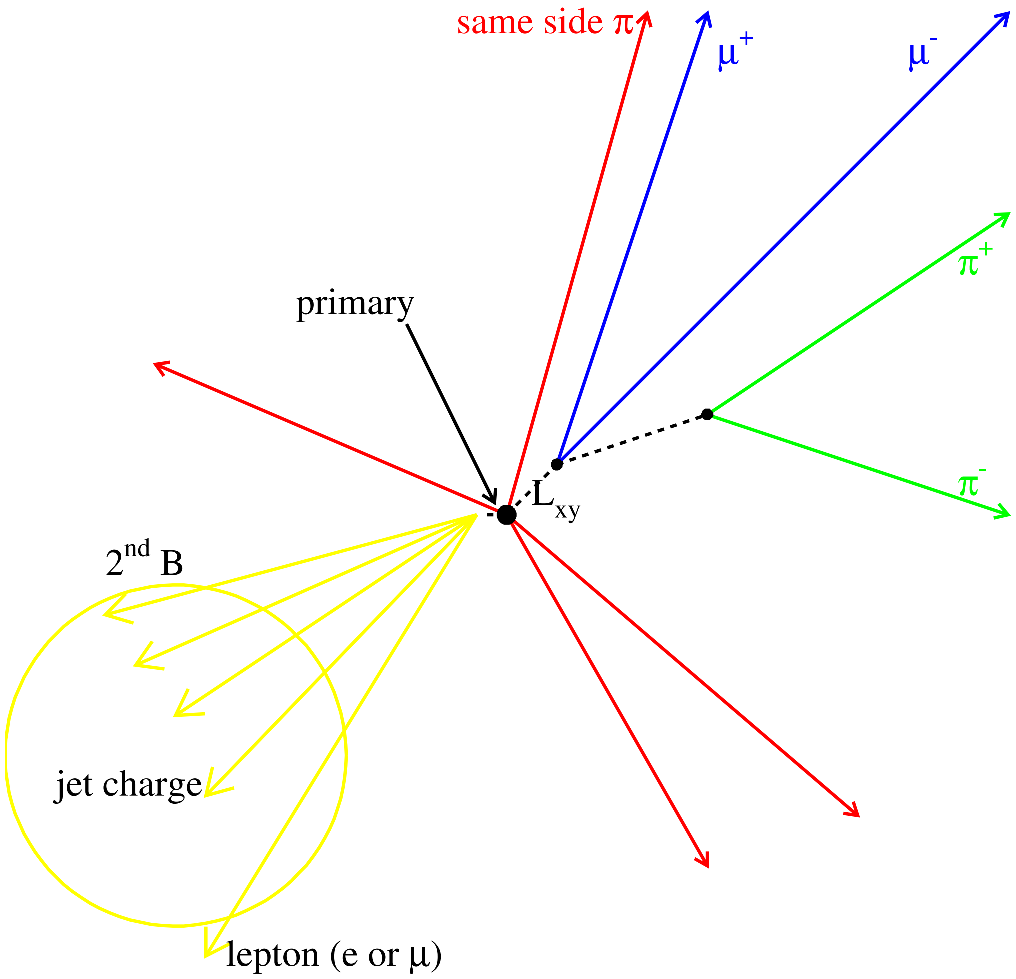
Yield = $(2 \times 10^{10}\mathrm{quarks}) \cdot (2 \times 10^{-8}) = 400$ **events**

Good news: **copious production of b quarks.**

Bad news: **environment is dense, signatures are difficult to reconstruct.**

Flavor Tagging

Determining the "flavor" (B^0 versus $\overline{B^0}$) at the time of production



- **same-side tagging**
- **opposite-side jet charge tagging**
- **opposite-side e and μ tagging**

Flavor Tagging

Classify a flavor tagging algorithm by two quantities:

- **tagging efficiency:** $\epsilon = N_{tag}/N_{tot}$
- **tagging dilution:** $\mathcal{D} = (N_R - N_W)/(N_R + N_W)$

$\rightarrow$ N_R**(**N_W**) number of right(wrong) sign tags.**

$\rightarrow$ $N_R + N_W = N_{tag}$

The statistical error on a measured asymmetry:

$$\delta A \propto \frac{1}{\sqrt{\epsilon \mathcal{D}^2 N_{tot}}}$$

$\epsilon \mathcal{D}^2$ **is the "effective tagging efficiency"**

- **typical** $\epsilon \mathcal{D}^2 \sim 1\%$

Flavor Tagging Example

We have a sample of 200 events.

- 100 **events are tagged**
- **efficiency** $\Rightarrow \epsilon = N_{tag}/N_{tot} = 100/200 = 50\%$

Of those 100 tagged events:

- 60 **are right-sign**
- 40 **are wrong-sign.**
- **dilution** $\Rightarrow \mathcal{D} = (60-40)/(60+40) = 20\%$

Effective tagging efficiency:

- $\epsilon\mathcal{D}^2 = (0.50) \cdot (0.20)^2 = 2\%$

The statistical power of our sample:

- $N\epsilon\mathcal{D}^2 = 4$ **"perfectly tagged" events**

The flavor tagging penalty is severe.

Opposite Side Tagging

Initial state: produce $b\bar{b}$

For this slide, assume:

- $b \rightarrow \overline{B^0} \rightarrow J/\psi K^0_S$
- $\bar{b} \rightarrow B_2$ **(**$B_2 = B^0, B^+, B^0_s$**,etc.)**

We try to use the other B_2 to identify the initial flavor.

- **Soft Lepton Tagging (SLT)**

  $\rightarrow$ **looking for** $B_2 \rightarrow \ell + X$

  $\rightarrow$ ℓ **= electrons and muons**

  $\rightarrow$ **very high dilution, very low efficiency**

- **Jet Charge Tagging (JetQ)**

  $\rightarrow$ **looking for** $B_2 \rightarrow X$

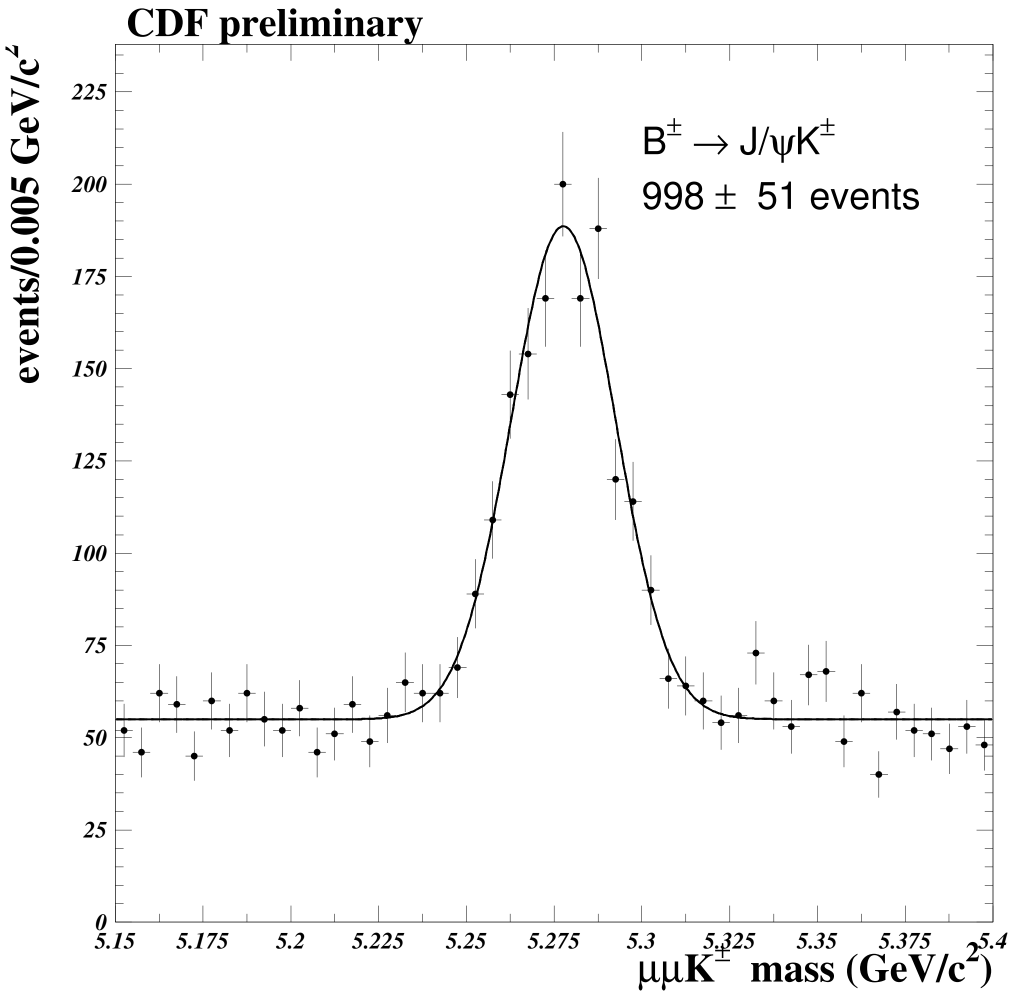
  $\rightarrow$ **find a "jet" of charge tracks**

  $\rightarrow$ **momentum weighted charge sum** $\Rightarrow$ **correlated with** B **or** $\bar{B}$

  $\rightarrow$ **higher efficiency, but lower dilution**

Calibration of Taggers

We use the $B^{\pm} \to J/\psi K^{\pm}$ sample to calibrate the flavor tagging algorithms:

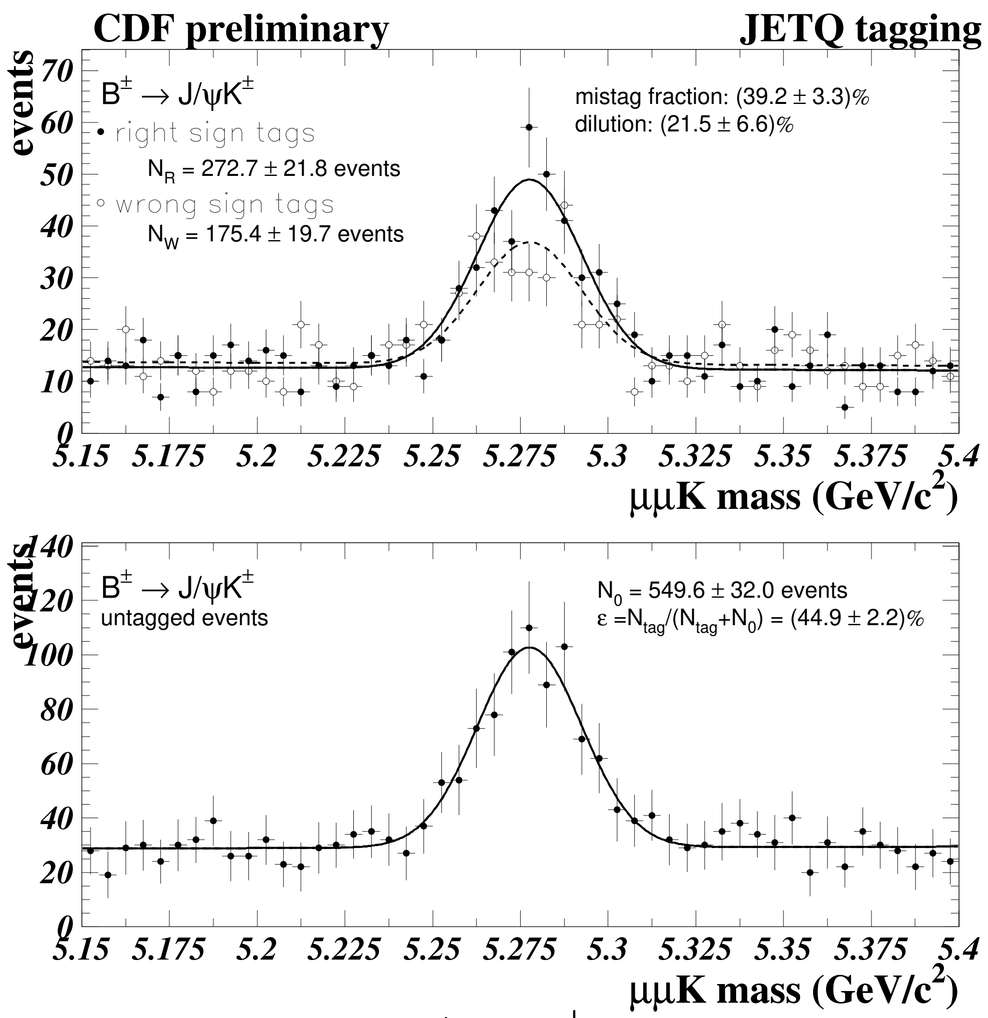


- **since we are fully reconstructing a charged B decay, we already know the answer**

  (charge of the $K^{\pm}$ tells us B or $\overline{B}$)

- **the decay mode and trigger are virtually identical to $B \to J/\psi K^0_S$**

Calibration of Jet Charge Tag



From a sample of 998 $J/\psi K^{\pm}$ events:

- **273 right-sign events**
- **175 wrong-sign events**

Tagging efficiency: $\epsilon = N_{tag}/N_{tot} = (44.9 \pm 2.2)\%$

Tagging dilution: $\mathcal{D} = \frac{N_R - N_W}{N_R + N_W} = (21.5 \pm 6.6)\%$

mistag fraction: $w = (39.2 \pm 3.3)\%$

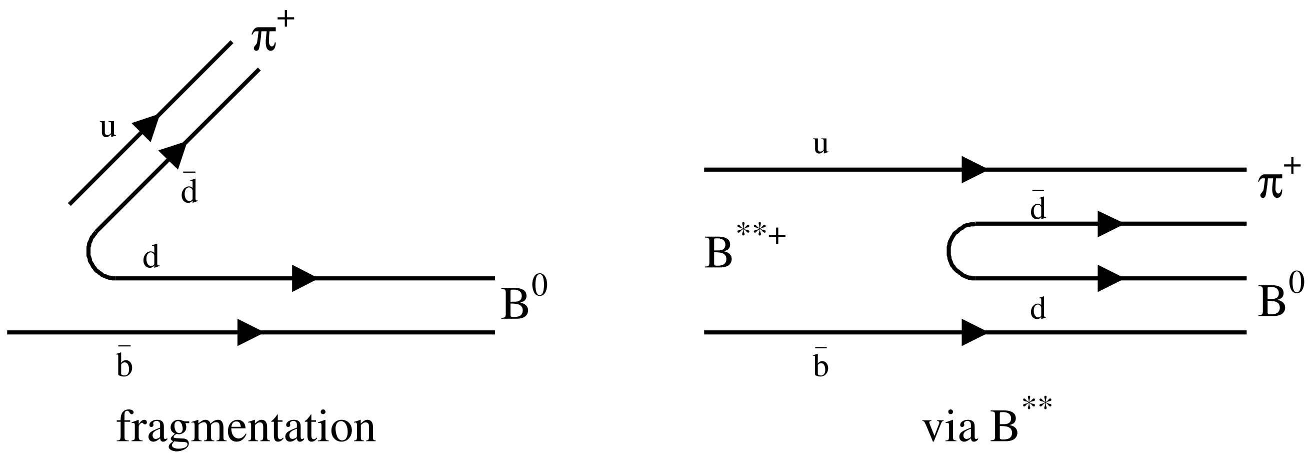
"Same-side" Tagging

Problems with opposite-side tagging:

- **opposite b-hadron is central (within detector acceptance) only 50% of the time**
- **if opposite b-hadron is B^0 or B_s, mixing degrades ability to tag**

Same Side Tagging (SST):

- **use charged particles around B meson to get the b flavor**
  - **correlation could be through fragmentation**
  - **or through excited states (B^{**})**



- **high tagging efficiency ($\sim 70\%$)**
- **no requirement on second B**

Summary of Flavor Tagging Algorithms

type	tagger	class	efficiency(ϵ)	dilution($\mathcal{D}$)
same-side	same-side	SVX μ	35.5 ± 3.7	16.6 ± 2.2
	same-side	non-SVX μ	38.1 ± 3.9	17.4 ± 3.6
opposite side	soft lepton	all events	5.6 ± 1.8	62.5 ± 14.6
	jet charge†	all events	40.2 ± 3.9	23.5 ± 6.9

† an SLT tag overrides jet-charge

The tagging algorithms all have similar power:

tagger	$\epsilon\mathcal{D}^2$
same-side	2.1 ± 0.5
jet charge	2.2 ± 1.3
soft lepton	2.2 ± 1.0

When we combine these flavor tagging algorithms (accounting for correlations and double tags) we measure:

$$\epsilon\mathcal{D}^2 = (6.3 \pm 1.1)\%$$

Which means that, after tagging, a sample of 400 events has the statistical power of about 25 'perfectly tagged' events.

Combining Flavor Tags

Example: same-side tag ($\mathcal{D} = 16.6\%$) and jet charge tag ($\mathcal{D} = 21.5\%$)

if the tags agree:

$$\mathcal{D}_{eff} = (D_1 + D_2)/(1 + D_1 D_2)$$

$$\mathcal{D}_{eff} = (0.215{+}0.166)/(1{+}(0.166)(0.215)) = 36.8\%$$

if they disagree:

$$\mathcal{D}_{eff} = (D_1 - D_2)/(1 - D_1 D_2)$$

$$\mathcal{D}_{eff} = (0.215{-}0.166)/(1{-}(0.166)(0.215)) = 5.1\%$$

and the sign of the tag would come from the jet charge tag.

Each event is weighted by its dilution in the fit.

Tagging Asymmetries

We explicitly account for the tagging algorithms which are not completely charge symmetric. An asymmetric tagging algorithm could arise from:

- **a charge bias in tracking efficiency**
- K^+N **versus** K^-N **cross section differences**
- **charge asymmetric background (beampipe spallation)**

When allowing for this asymmetry, we end up with four tagging parameters for each tagging method:

- D_+**: the dilution for (+) tags**
- D_-**: the dilution for (-) tags**
- ϵ_+**: the tagging efficiency for (+) tags**
- ϵ_-**: the tagging efficiency for (-) tags**

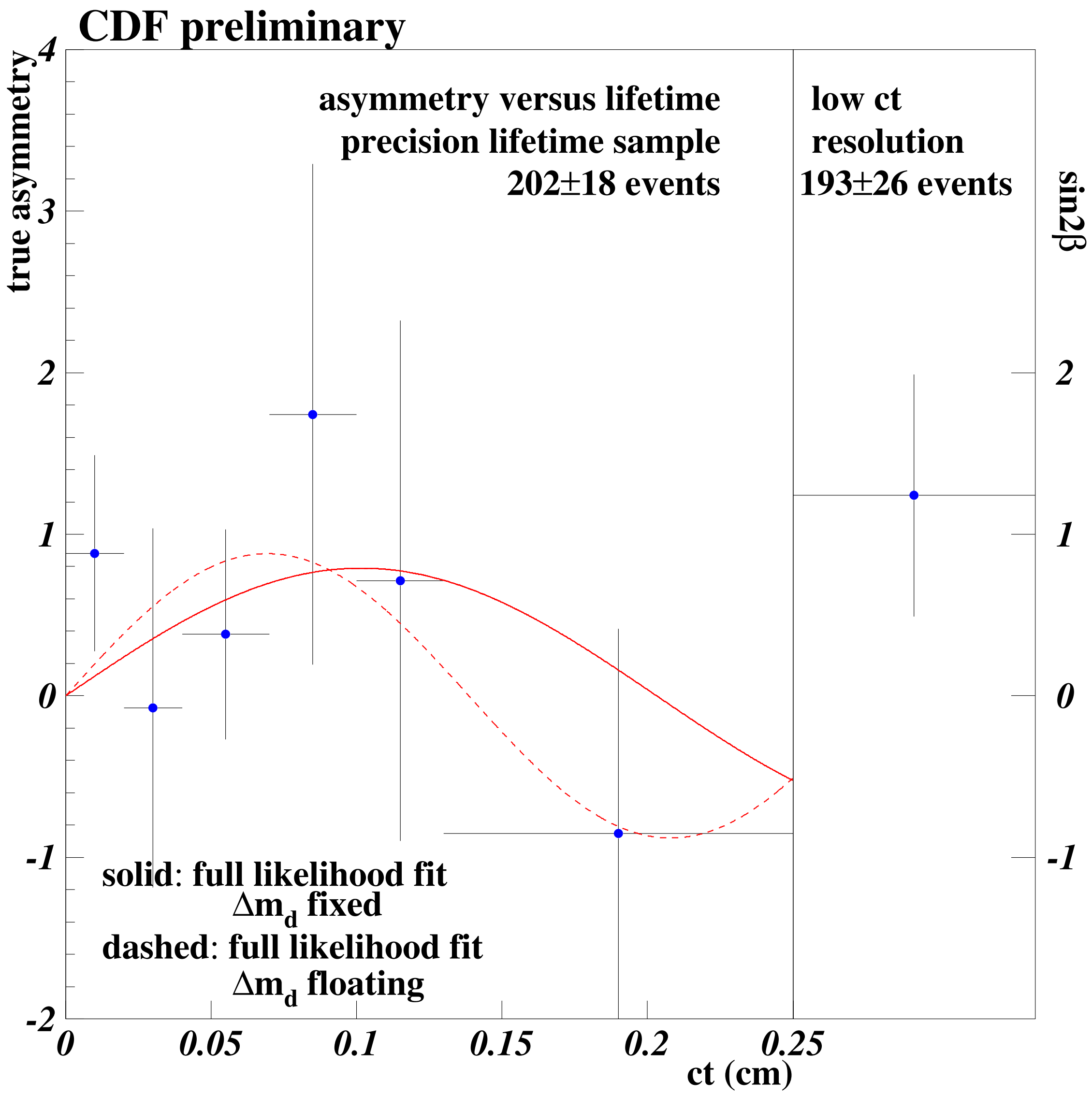
Outline

1. **Introduction:**
   - **Charged Current Decays**
   - **the CKM Matrix**
   - $B/\overline{B}$ **Mixing**
2. CP **violation**
   - **Introduction**
   - **the** $J/\psi K_S^0$ **Mode**
3. **the Measurement of** $\sin 2\beta$
   - **the Fermilab Tevatron**
   - **the CDF Detector**
   - **the** $J/\psi K_S^0$ **Sample**
   - **Flavor Tagging**
   - **Results**
4. **Outlook: Other** CP **Modes**
5. **Summary**

Results

We measure:

$$\sin 2\beta = 0.79 \begin{array}{l} +0.41 \\ -0.44 \end{array} \text{(stat. + syst.)}$$



$$A = \sin 2\beta \sin(\Delta m_d)$$

Systematic Uncertainties

Specifically splitting off the systematic error, we find:

$$\sin 2\beta = 0.79 \pm 0.39(\mathrm{stat}) \pm 0.16(\mathrm{syst})$$

Summary of systematic error evaluation:

parameter	evaluated	$\delta \sin 2\beta$
tagging dilution	in fit	0.16
tagging efficiency	in fit	
Δm_d	in fit	0.01
τ_{B^0}	in fit	0.01
m_B	refit	0.01
trigger bias	external	negligible
K_L^0 regeneration	external	negligible

"Systematic" error dominated by $\delta\mathcal{D}$, which is statistics limited.

Float Δm_d

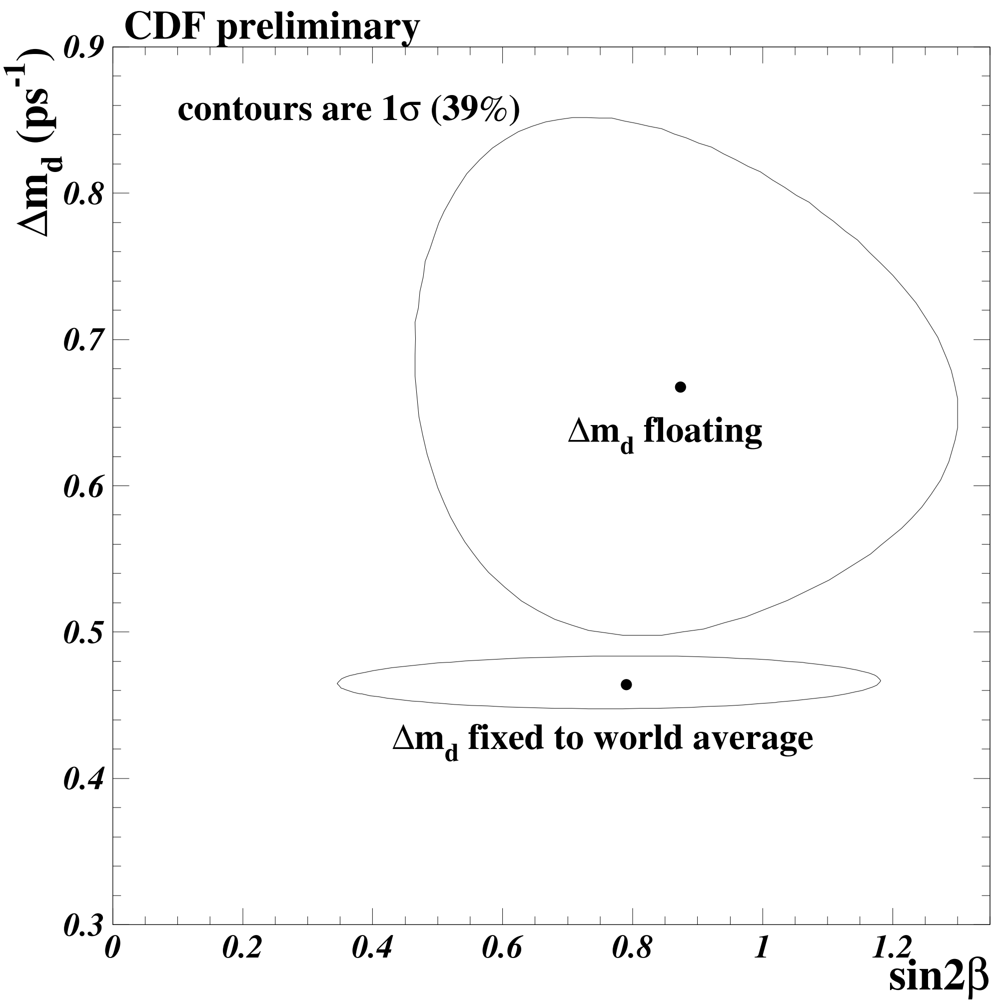
When we let Δm_d float in the fit, we measure:

$$\sin 2\beta = 0.88 \begin{array}{l} +0.44 \\ -0.41 \end{array}$$

and

$$\Delta m_d = 0.68 \pm 0.17\,\mathrm{ps}^{-1}$$

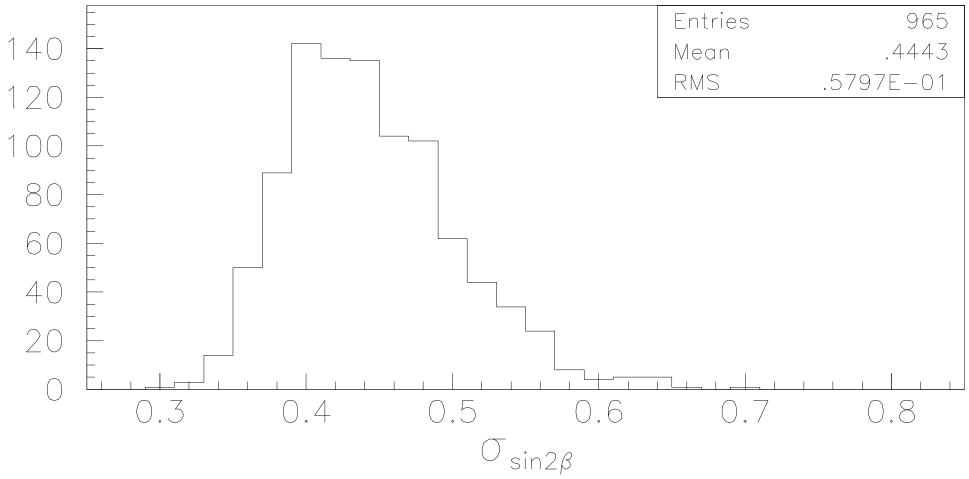
The 1σ contour:

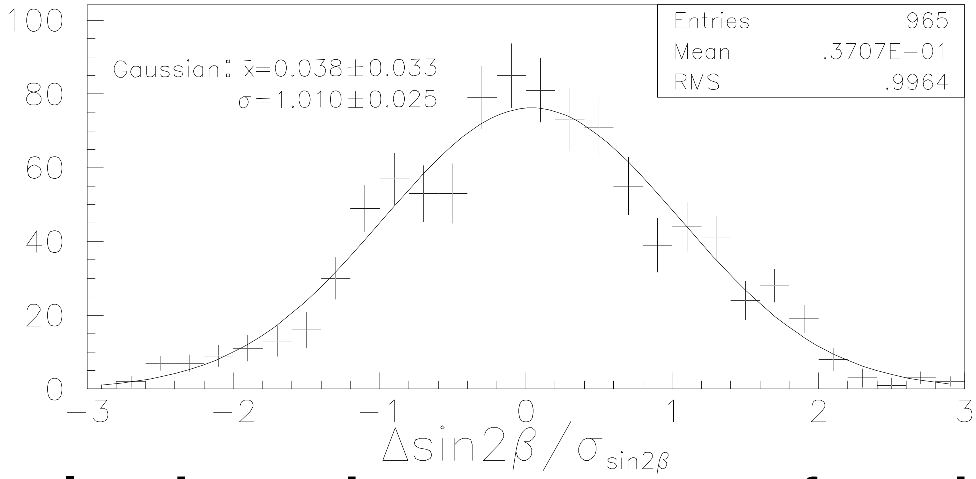


the PDG value is $\Delta m_d = 0.464 \pm 0.018\,\mathrm{ps}^{-1}$.

Toy Monte Carlo

The error on our result is $\delta \sin 2\beta = {}^{+0.41}_{-0.44}$. We use a "toy MC" to generate the relevant observables for many "experiments" to see if this error is reasonable:





The top plot shows that average error from the toy is 0.44, consistent with our measurement.

The bottom plot shows from the "pull" distribution that the error returned from the fit correctly estimates the uncertainty in the result.

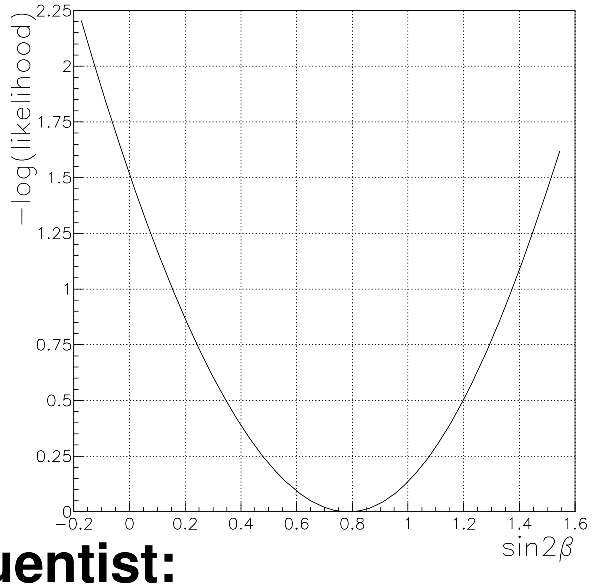
Limits

We measure:

$$\sin 2\beta = 0.79 \begin{array}{l} +0.41 \\ -0.44 \end{array} (\text{stat.} + \text{syst.})$$

(Note: this result is with Δm_d constrained to the world average.)

A scan of the likelihood function:



Feldman-Cousins frequentist:

- $0 < \sin 2\beta < 1$ **at** 93% CL

Bayesian (assuming flat prior in $\sin 2\beta$)

- $0 < \sin 2\beta < 1$ **at** 95% CL

Assume $\sin 2\beta = 0$
integrate Gaussian from $0.79 \to \infty$:

- **Prob($\sin 2\beta > 0.79$) =** 3.6%

Direct Measurements

- **OPAL (January '98)**

  D. Ackerstaff *et al.*, Euro.Phys.Jour. **C5**, 379 (1998).

  $\rightarrow \sin 2\beta = 3.2^{+1.8}_{-2.0}\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$

  $\rightarrow$ **from** $\sim 14\ B \rightarrow J/\psi K^0_S$ **decays**

- **CDF (February '99)**

  T.Affolder *et al.*, Phys.Rev.**D** (2000). hep-ex/9909003

  $\rightarrow \sin 2\beta = 0.79^{+0.41}_{-0.44}\,(\mathrm{stat.} + \mathrm{syst.})$

  $\rightarrow$ **from** $\sim 400\ B \rightarrow J/\psi K^0_S$ **decays**

- **ALEPH (November '99)**

  R.Forty *et al.*, ALEPH 99-099.

  $\rightarrow \sin 2\beta = 0.93^{+0.64}_{-0.88}\,(\mathrm{stat.})\ ^{+0.36}_{-0.24}\,(\mathrm{syst.})$

  $\rightarrow$ **from** $\sim 16\ B \rightarrow J/\psi K^0_S$ **decays**

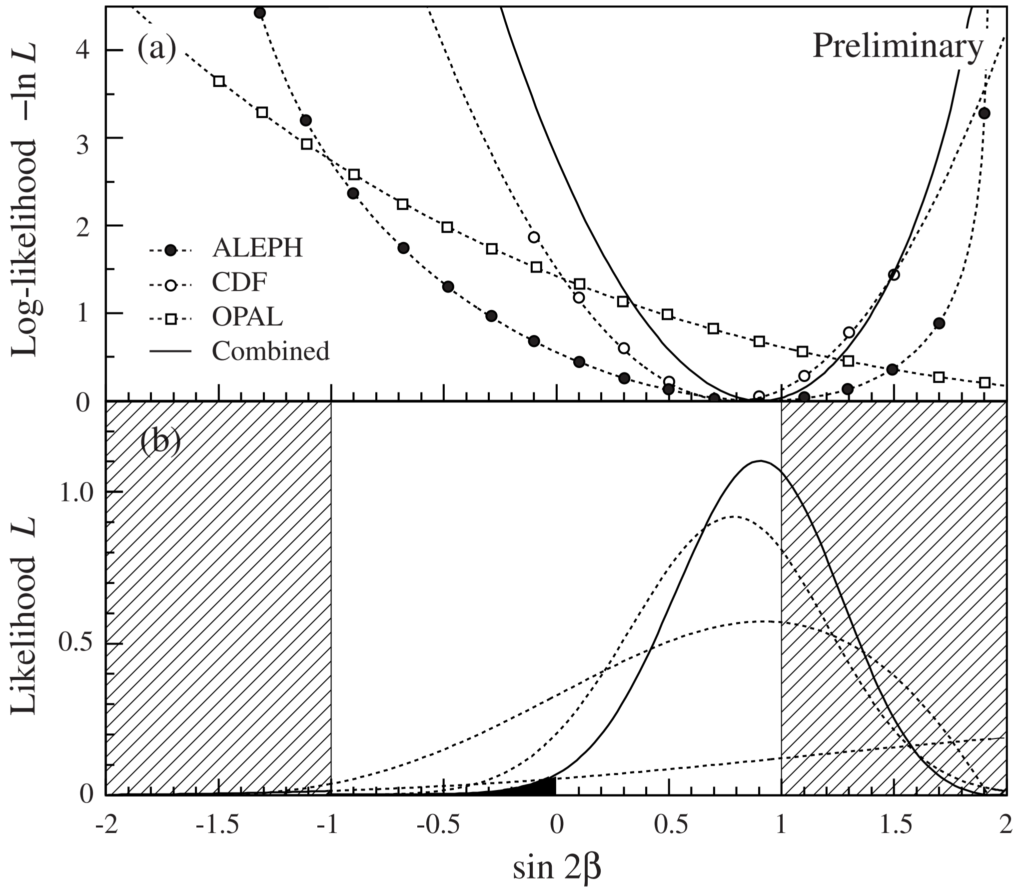
LEP measurements have much fewer events, but are able to do much better flavor tagging.

B **factories will do even better at flavor tagging.**

"Combined Result"

Combining: CDF + ALEPH + OPAL results

(R. Forty, ALEPH)



$$\sin 2\beta = 0.91 \pm 0.35$$

CDF result dominates the combined result.

Future Measurements of $\sin 2\beta$

The CDF analysis sees an "indication" that there is indeed CP violation in the B system, but we have not made a definitive observation.

Future experiments at the Tevatron and elsewhere will reduce the error on $\sin 2\beta$ by a factor of 10:

- e^+e^- **"B factories" at Cornell, SLAC(Stanford) and KEK(Japan)**

  $\rightarrow$ $e^+e^- \rightarrow B\overline{B}$ **at threshold**

- **fixed target at DESY (Germany)**

  $\rightarrow$ $pN \rightarrow b\overline{b}X$

- $p\overline{p}$ **at the Tevatron**

  $\rightarrow$ $p\overline{p} \rightarrow b\overline{b}X$

For example, each experiment expects $\delta(\sin 2\beta) \simeq 0.08 \Rightarrow$ world average uncertainty of $\delta(\sin 2\beta) \sim 0.03$, which is a precise test of the standard model.

Comparison of B Factory Expectations

Summary of SOME CP Violation Measurements for the next generation of B experiments after $\sim$1 year of running (at design luminosity):

		BELLE	BaBar	Hera-B	DØ	CDF
$\int \mathcal{L}dt\,(\mathrm{fb}^{-1})$		100	30	100	1	1
N($B \to \psi K^0_S$)		2000	1100	1500	4k	5k
$\delta(\sin 2\beta)$	ψK^0_S	0.080	0.098	0.13	0.20	0.12
	all modes	0.062	0.059	0.12	0.20	0.12
N($B \to \pi^+\pi^-$)		650	350	800	–	4.6k
$BR(B \to \pi^+\pi^-)^*$ ($\times 10^{-5}$)		1.3	1.2	1.5	–	0.5
$\delta(\sin 2\alpha)^\dagger$	$\pi^+\pi^-$	0.147	0.20	0.16	–	0.16
	all modes	0.089	0.085	0.16	–	0.16

* **assumed branching ratio**

CLEO measurement: $BR(B^0 \to \pi^+\pi^-) = (4.7^{+1.8}_{-1.5} \pm 0.6) \times 10^{-6}$

† **assuming that penguin contamination can be unfolded**

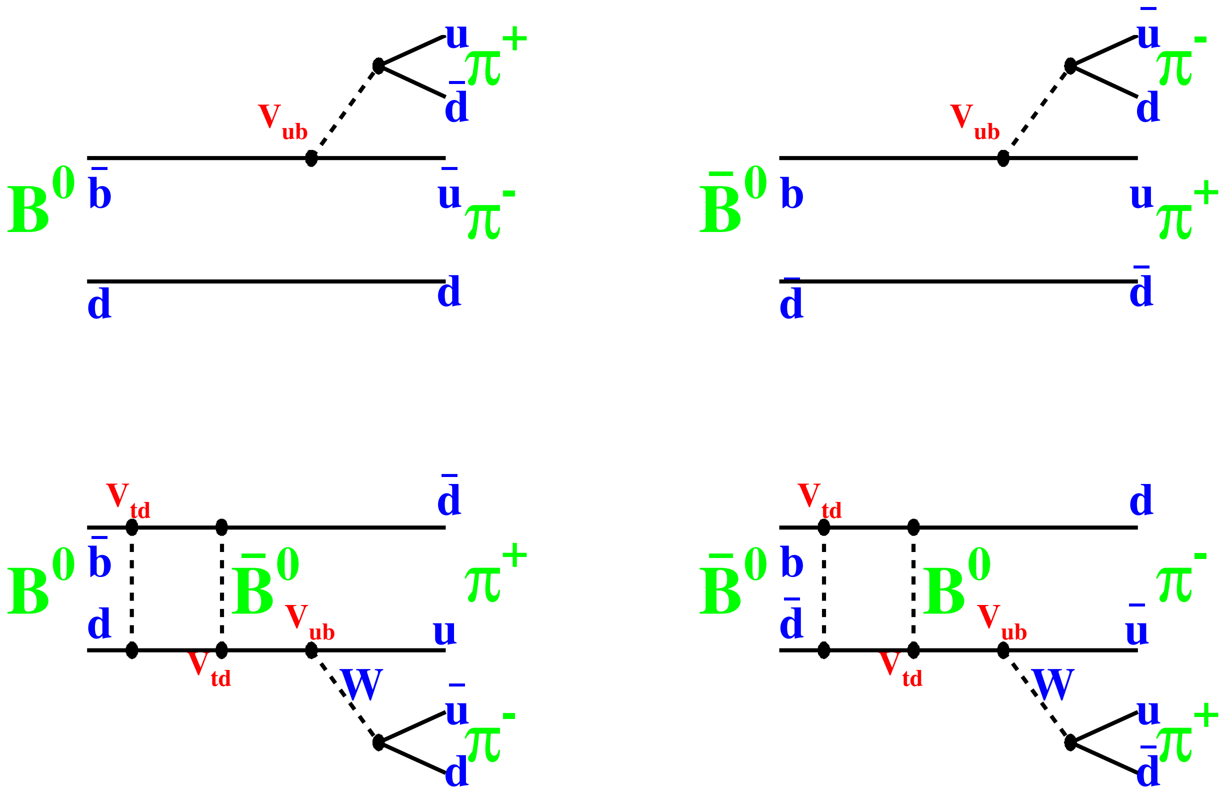
An incomplete list for EVERY experiment.

CLEO-III should not be forgotten:

- **Measure (or limit) the CP asymmetry in** $B^- \to D^0 K^- / \overline{D}^0 K^- / D_{CP} K^-$ **(**$sin2\gamma$**)**
- **measurements of $BR(B^0 \to K\pi)$ & $BR(B^0 \to \pi\pi)$ will help disentangle the penguin contribution to $B^0 \to \pi^+\pi^-$**

Other Decay Modes

Another interesting CP violation mode is in the two body decay $B \to \pi^+\pi^-$:



In this case, there is a phase β coming from the mixing (just like the $J/\psi K^0_S$ final state.)

But there is an additional phase γ coming from the the $b \to u$ (V_{ub}) transition.

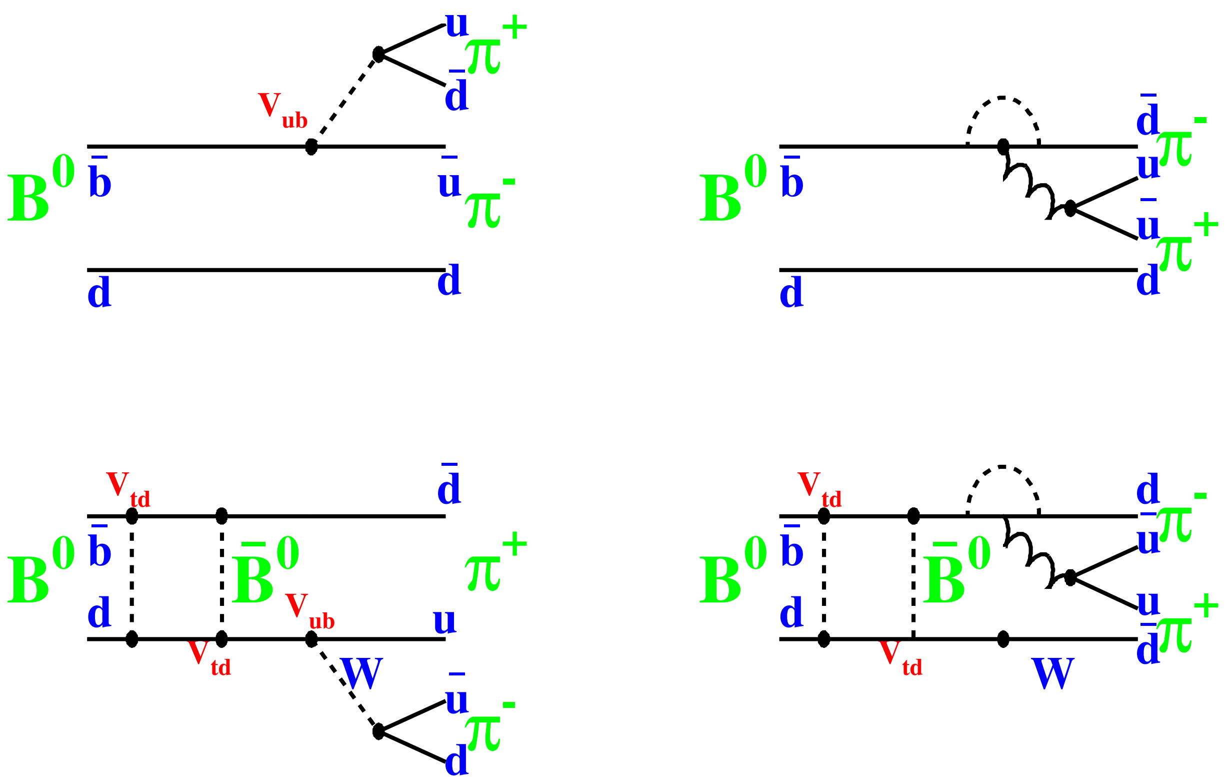
Phase is then $\beta + \gamma$ and CP asymmetry is proportional to: **($\alpha + \beta + \gamma = \pi$)**

$$\sin 2\alpha$$

However....

Penguin Contamination

In fact, there is another set of diagrams which contribute to this mode: (consider inital B^0 here)



The penguin decay is now known to be significant.

There is in fact interference between the tree and penguin decays, as well as the unmixed and mixed diagrams.

This implies that there is a "direct" CP violation component in the $B \to \pi^+\pi^-$ mode.

It complicates the extraction of CKM information from this mode.

Other Interesting/Important Measurements

To over constrain the triangle and further test/understand the physics of the CKM matrix, additional measurements will be important:

- B_s^0 **mixing**
- **improvement in** V_{ub}
- **the angle** γ **(difficult)**
- β **and** α **in other modes**
- **rare** B **decays:**

  $\rightarrow\ B^+ \rightarrow \mu^+\mu^-K^+$

  $\rightarrow\ B^0 \rightarrow \mu^+\mu^-$

  $\rightarrow\ b \rightarrow s\gamma$
- **the** B_c **meson production and decay**
- B **baryon (**$\Lambda_b = |udb>$**) production and decay**

Summary

The ongoing program is to overconstrain the CKM matrix (and the unitarity triangle) to further understand and (hopefully) spot inconsistencies which point to physics beyond the standard model.

To fully understand the mechanism behind weak decays, the CKM matrix and CP violation, we will need a number of measurements using a number of techniques.

This program will require important measurements at both e^+e^- and hadron machines.

Conclusion

Over 35 years since the observation of CP violation in the neutral kaon system.

We are now at the threshold of seeing and studying CP violation in another system (neutral B system).

Over the next several years, additional measurements in the K and B systems will help to shed light on the fundamental mechanisms behind CP violation.

It's starting to get interesting!

Stay tuned!