
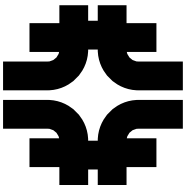

# $CP$ Violation in the $B$ System

## An Experimental View

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**February 17, 2000**

# 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<br>0 |
| | **free particles** | | | |
| **Quarks:** | | | | |
| | $\begin{pmatrix} u \\ d \end{pmatrix}$ | $\begin{pmatrix} c \\ s \end{pmatrix}$ | $\begin{pmatrix} t \\ b \end{pmatrix}$ | +2/3<br>-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 $B$east so interesting?

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

  $\rightarrow$ **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**

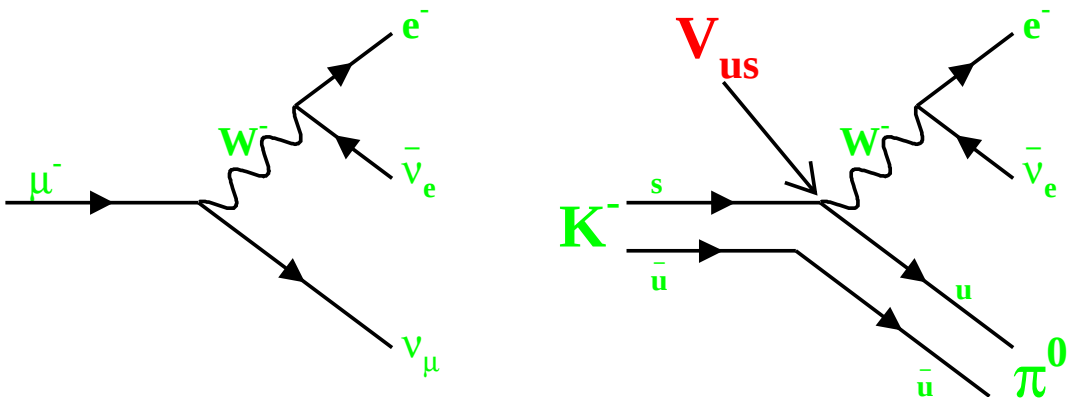
- **expected to show LARGE** $CP$ **violating effects**

  $\rightarrow$ **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**

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

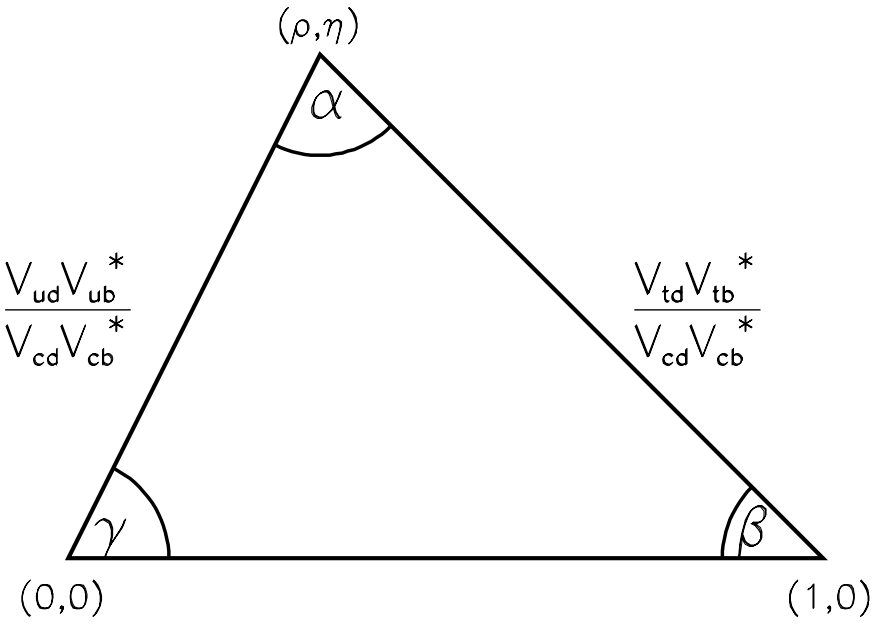
**is the Cabibbo-Kobayashi-Maskawa (CKM) Mixing Matrix which rotates quark mass eigenstates into weak eigenstates.**

# The Cabibbo-Kobayashi-Maskawa Matrix

**The Wolfenstein parameterization:**

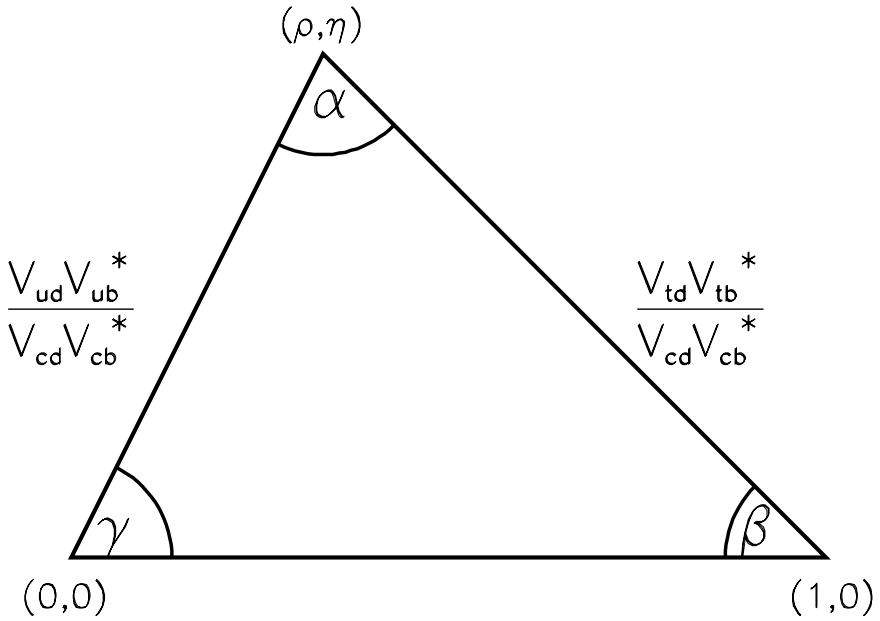
$$V \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- $\lambda = \sin\theta_C$, **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** $\Rightarrow V^\dagger V = V V^\dagger = 1$

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

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

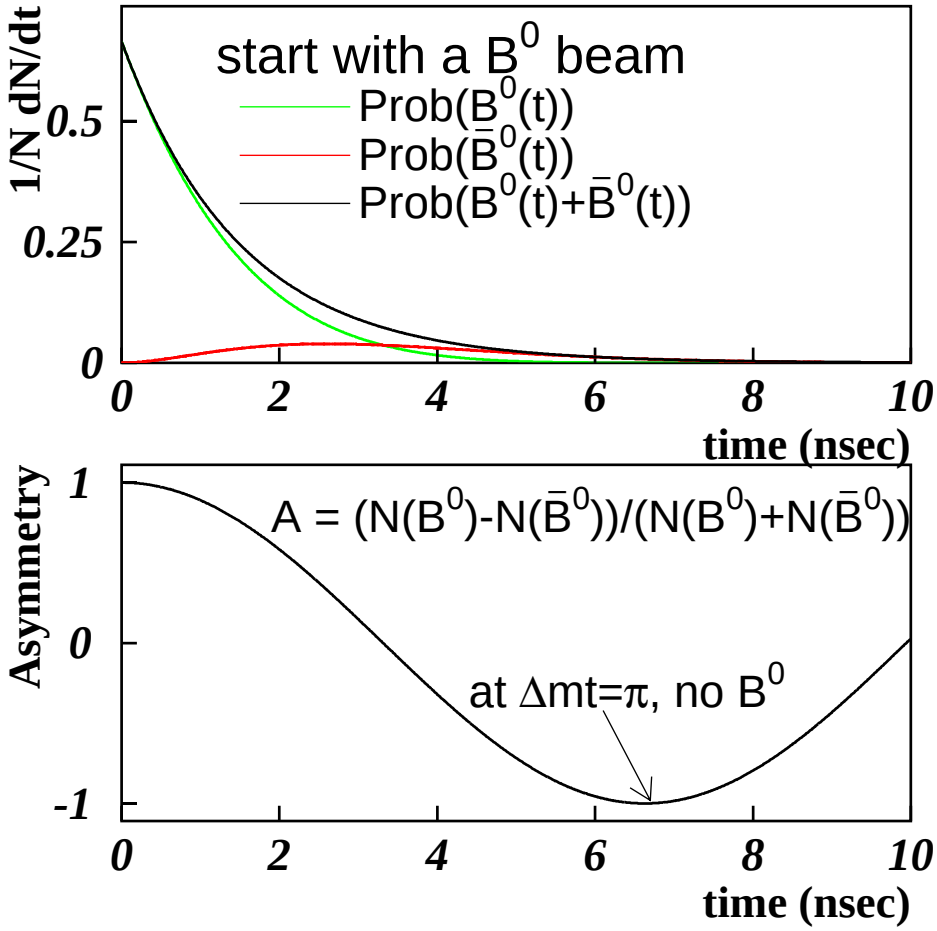
**This relation is quite useful because each term is of order $\lambda^3$.**

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

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

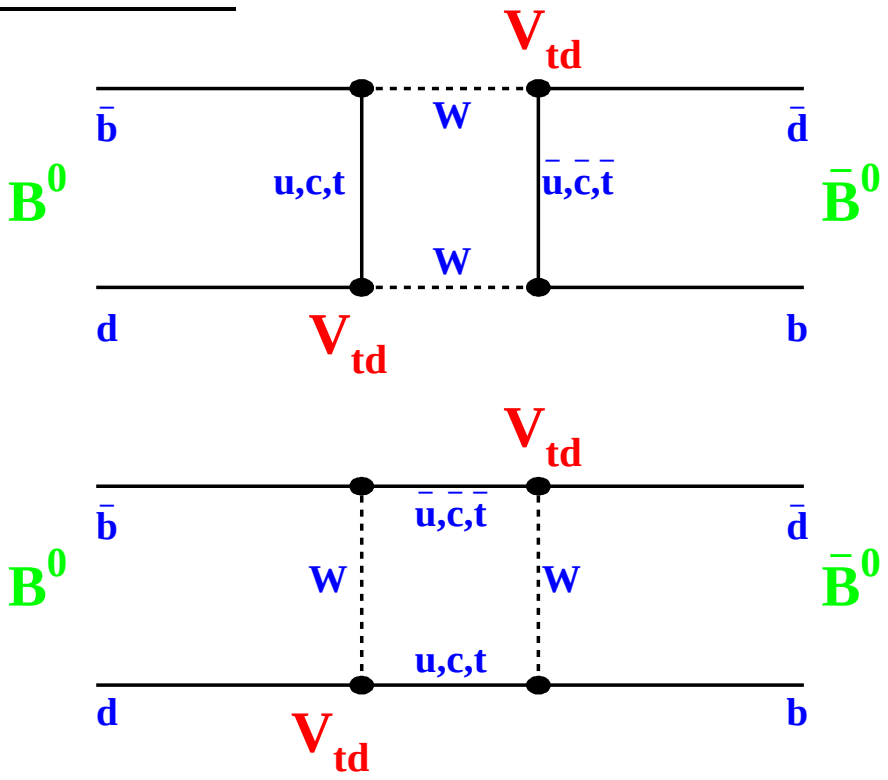
$$P(B^0(t)) = \frac{1}{2\tau}e^{-\frac{t}{\tau}}(1+\cos(\Delta m_d t))$$

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




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

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




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

$$B_H^0, B_L^0 : \text{Mass Eigenstates}$$

$$\Delta m_d = m_H - m_L$$

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

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

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

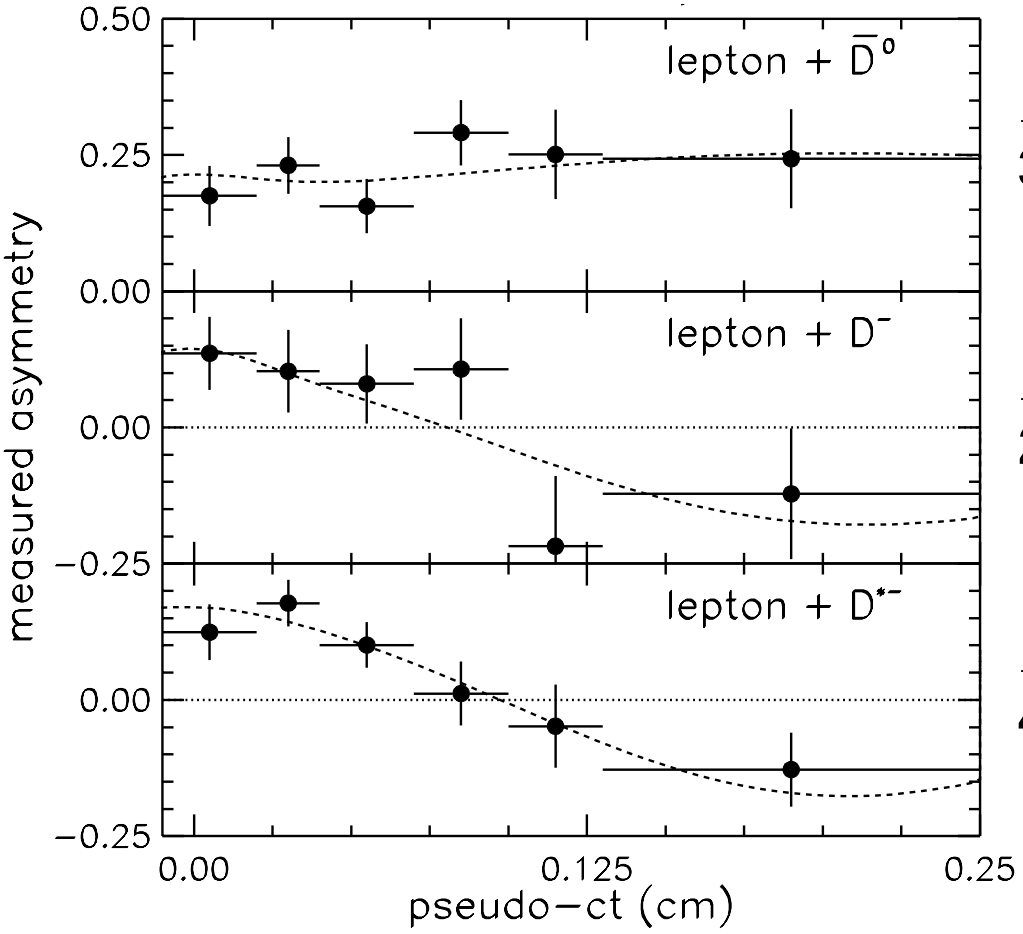
$$P(B^0(t)) \simeq \frac{1}{2}\Gamma e^{-\Gamma t}( \quad 1 \quad + \cos(\Delta m_d t))$$

**$B^0$ fully mixes to $\overline{B^0}$ after $\Delta m t = \pi \simeq 4.4$ 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*
   - $P\psi(\vec{r}) \rightarrow \psi(-\vec{r})$
   - **left-handed $\Rightarrow$ right-handed**
   - $P|e_L^- > \rightarrow |e_R^- >$
2. **charge conjugation:** $C$ *particle $\rightarrow$ antiparticle*
   - **particle $\rightarrow$ antiparticle**
   - $C|p > \rightarrow |\overline{p} >$
3. **time reversal:** $T$ *run the film backwards*
   - $T\psi(t) \rightarrow \psi^*(-t)$

---

**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**

$\uparrow P$ $\uparrow C$

**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:**

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

**where**

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

**and $J/\psi K_S^0$ is a CP eigenstate:**

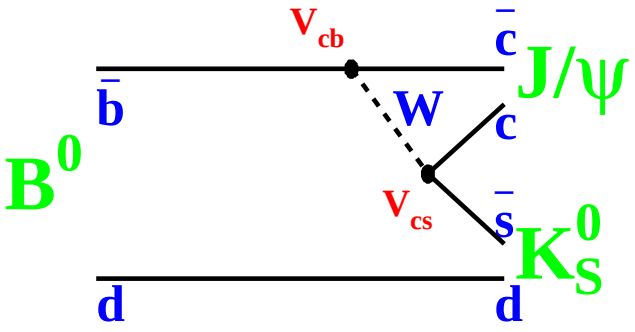
$$CP|J/\psi K_S^0 >= -|J/\psi K_S^0 >$$

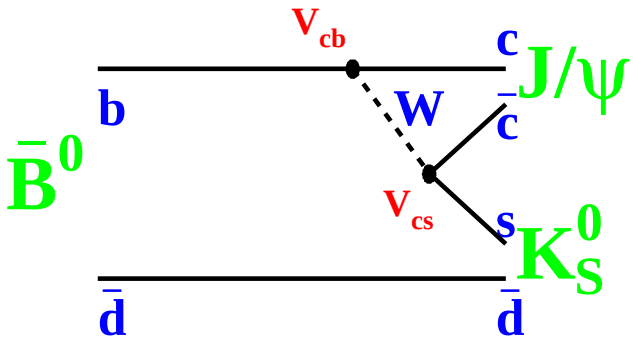
# "Mixing Induced" $CP$ Violation

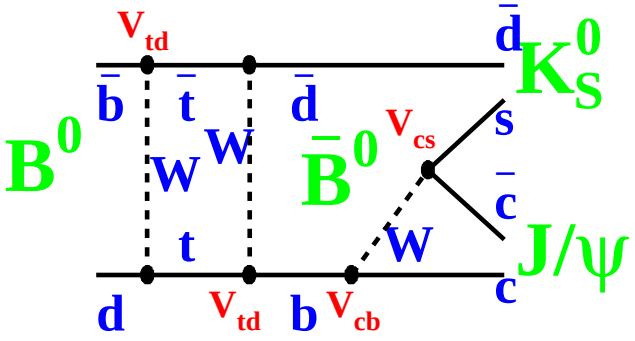
**Two paths to the same final state:**

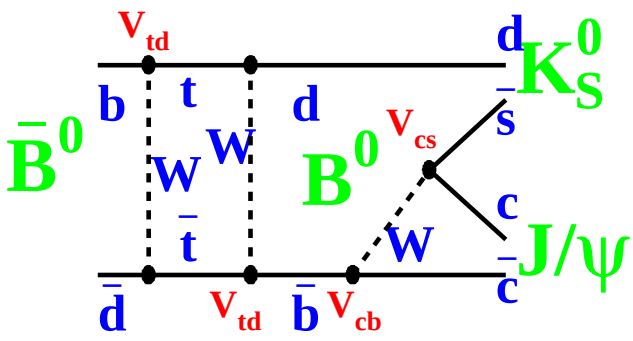
- **direct decay ($B^0 \to J/\psi K^0_S$)**
- **mixed decay ($B^0 \to \overline{B^0} \to J/\psi K^0_S$)**

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



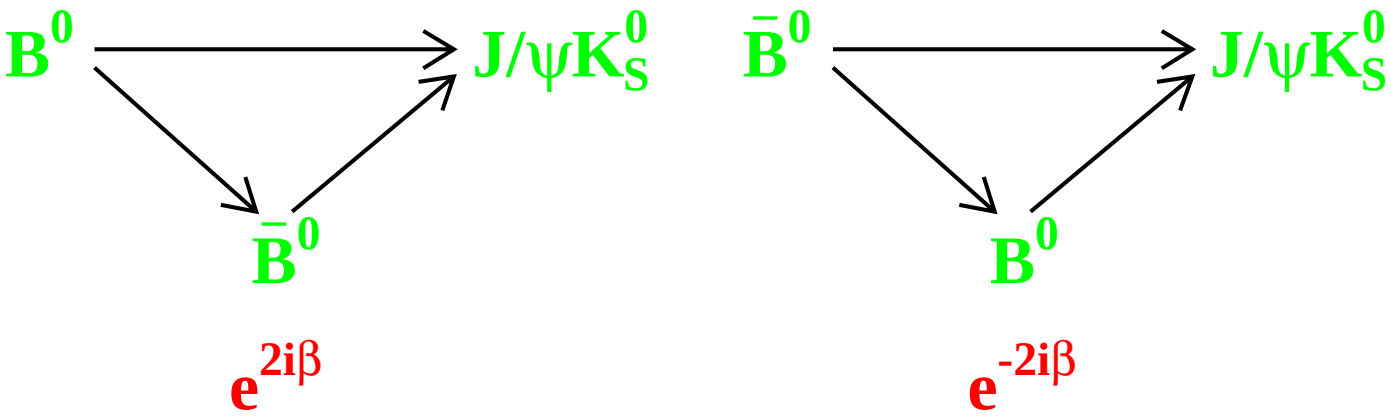




↑ **produce $B^0$ at $t = 0$**

↑ **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 $2\beta$ arises from the interference.**

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

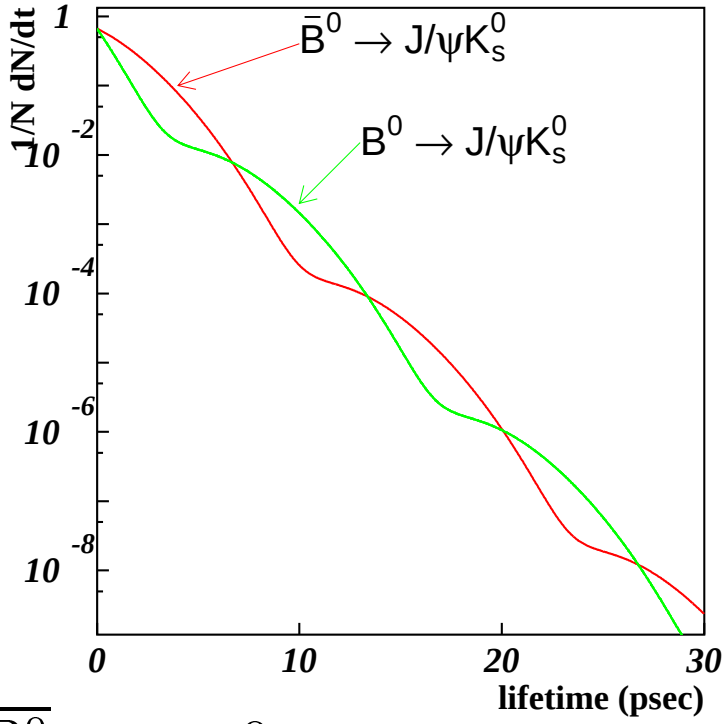
$$\frac{dN}{dt}(\overline{B^0} \to J/\psi K_s^0) \propto e^{-t/\tau}(1 + \sin 2\beta \sin \Delta m t)$$

**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 $t = 0$:**

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

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

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

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

# $CP$ Violation

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

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

↑ amplitude ↑ mixing

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

**(Note: $\Delta m_d$ 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 $\sin 2\beta$

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

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

**time integrated:**

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

$$A_{CP} = \frac{N(\overline{B}^0 \to \psi K_S^0) - N(B^0 \to \psi K_S^0)}{N(\overline{B}^0 \to \psi K_S^0) + N(B^0 \to \psi K_S^0)}$$

$$A_{CP} = \frac{\Delta m_d \tau_B}{1 + (\Delta m_d \tau_B)^2} \cdot \sin 2\beta$$

$$A_{CP} \simeq 0.47 \sin 2\beta$$

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

# Assumptions

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

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

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

- $\Delta\Gamma = \Gamma_H - \Gamma_L \simeq 0$
- $B^0 \to J/\psi K^0_S$ **via penguin is small**
  - $\to$ $g \to c\bar{c}$ **is mass-suppressed**
  - $\to$ **if present, complicates** $A_{CP}(t)$ **with** $\cos(\Delta m t)$ **term**
- $K^0_S$ **is** $100\%$ $CP$ **even**
- $N(B^0) = N(\overline{B^0})$ **at** $t = 0$
  - $\to$ $p\overline{p} \to b\bar{b}X$
  - $\to$ **strong interaction preserves bottomness**

# 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**
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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!**

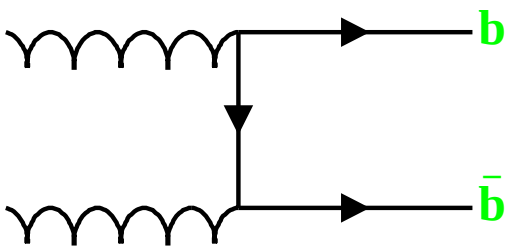
**The Tevatron produces** $10^{10}$ $b\overline{b}$ **pairs in a year.**

# $B$ Physics at the Tevatron

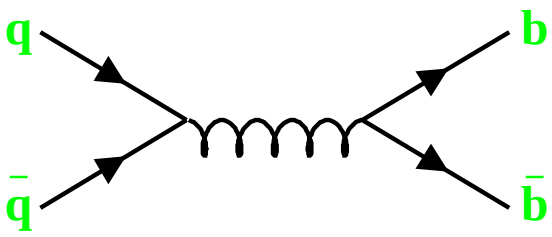
**Strong interaction produces $b$ quarks:**

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

*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**

- **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:**
    $\sim 10\,\mathrm{MeV/c^2}$
  - **Muon systems, calorimeter**
    **crucial for triggering and lepton identification**

# Triggering

**$p\overline{p}$ 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** $\sim 10$**-**$15\ \mu\mathrm{s}$
  - $\rightarrow$ $2\,\mathrm{kHz}$ **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 $6 \times 10^{12}$ $p\overline{p}$ 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**

# $B \to J/\psi K^0_S$ Event Selection

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

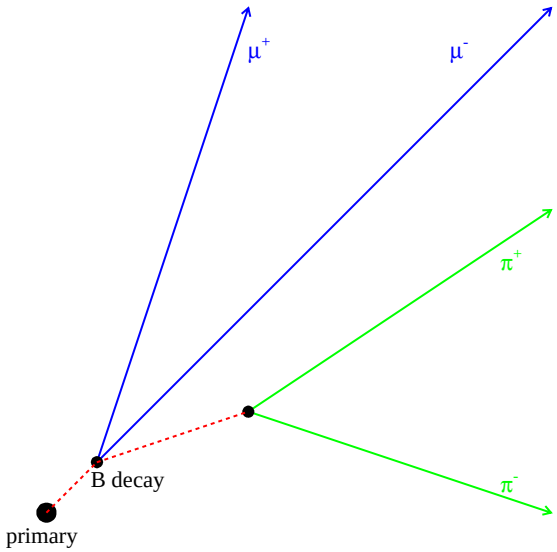
  $\to$ **$\mu$ = central track + muon chamber track**

- **look for $K^0_S \to \pi^+\pi^-$**

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

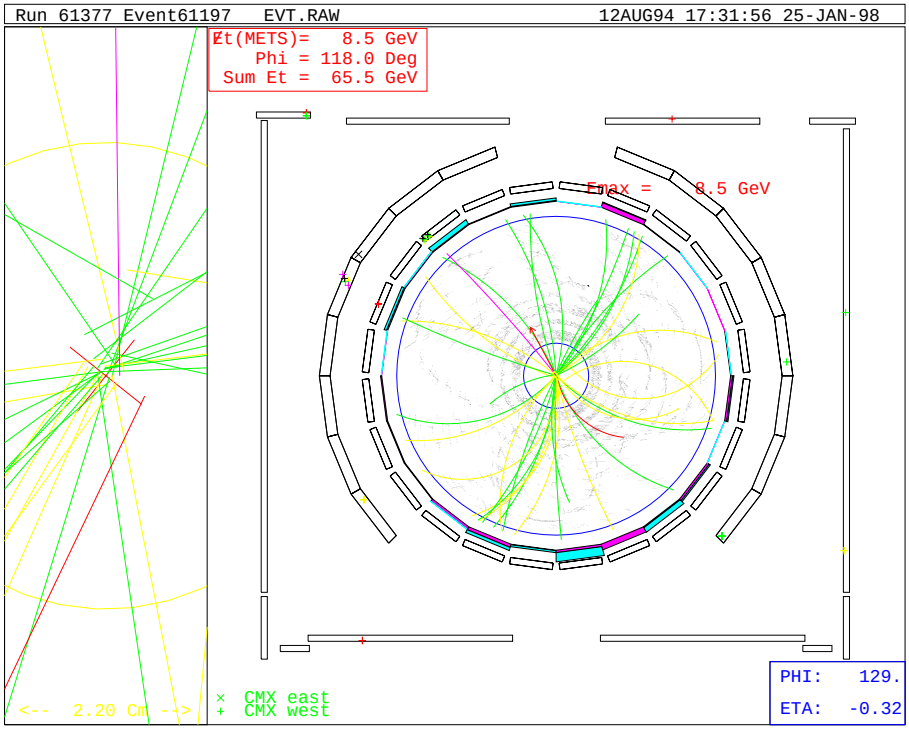
- **perform 4-track fit assuming $B \to J/\psi K^0_S$:**

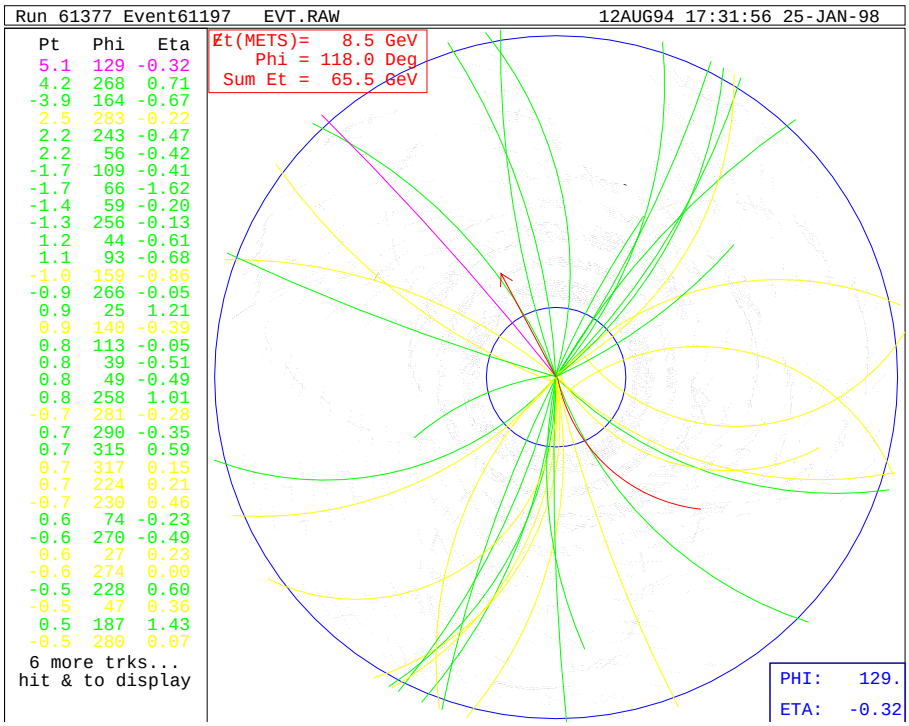
  - **$\pi^+\pi^-$ constrained to PDG $K^0_S$ mass**
  - **$K^0_S$ "points" to $B$ ($J/\psi$) vertex**
  - **$\mu^+\mu^-$ constrained to PDG $J/\psi$ mass**
  - **$B$ candidate "points" back to primary vertex**




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

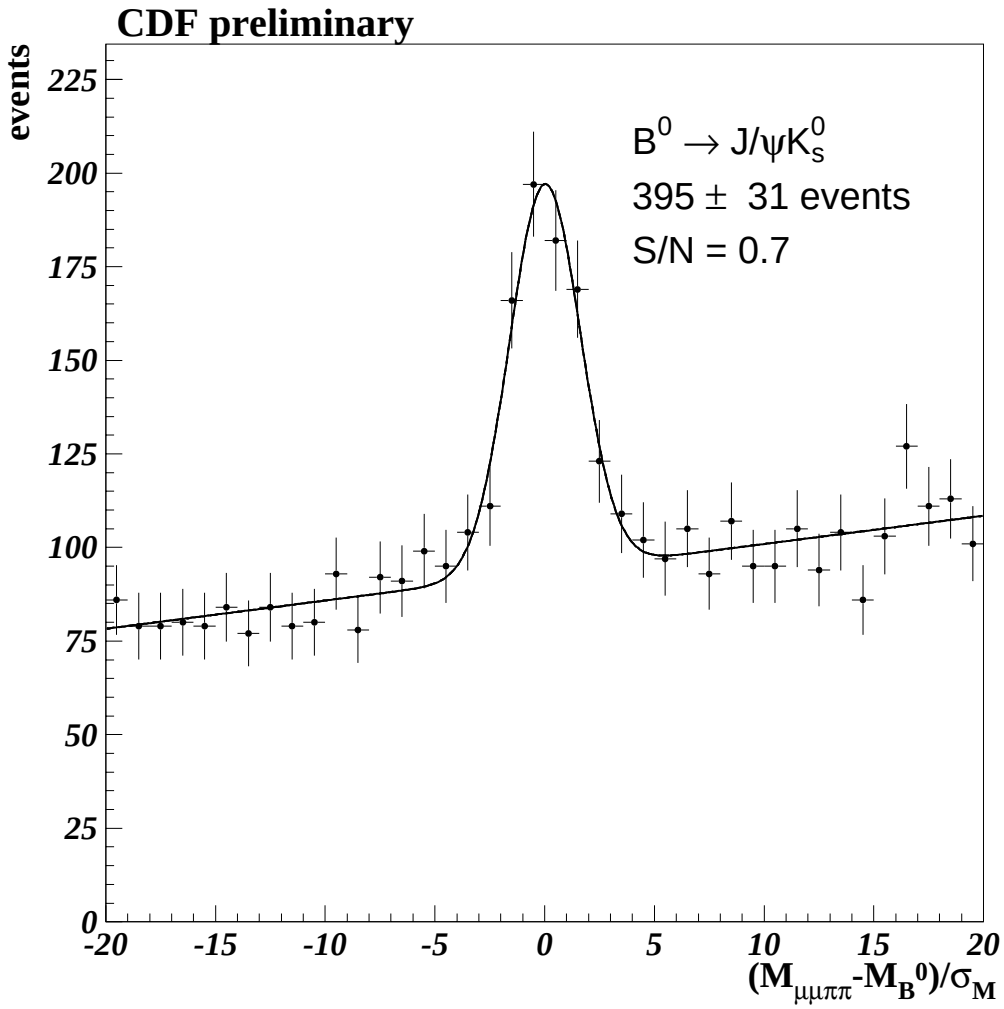
# $B \to J/\psi K^*$ Candidate Event



# Event Yield

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




- $395 \pm 31$ **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**

  $\sigma_m$ **the experimental error on that fitted mass.**

  $m_{B^0} = 5.2792\,\mathrm{GeV/c^2}$ **(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%** |
| $B^0 \to J/\psi K^0_S$ | **0.04%** |
| $J/\psi \to \mu^+\mu^-$ | **6%** |
| $K^0_S \to \pi^+\pi^-$ | **67%** |
| **tracks are in the detector acceptance** | **0.4%** |
| **total "efficiency"** | $\mathbf{2 \times 10^{-8}}$ |

**Yield = events $\times$ "efficiency"**

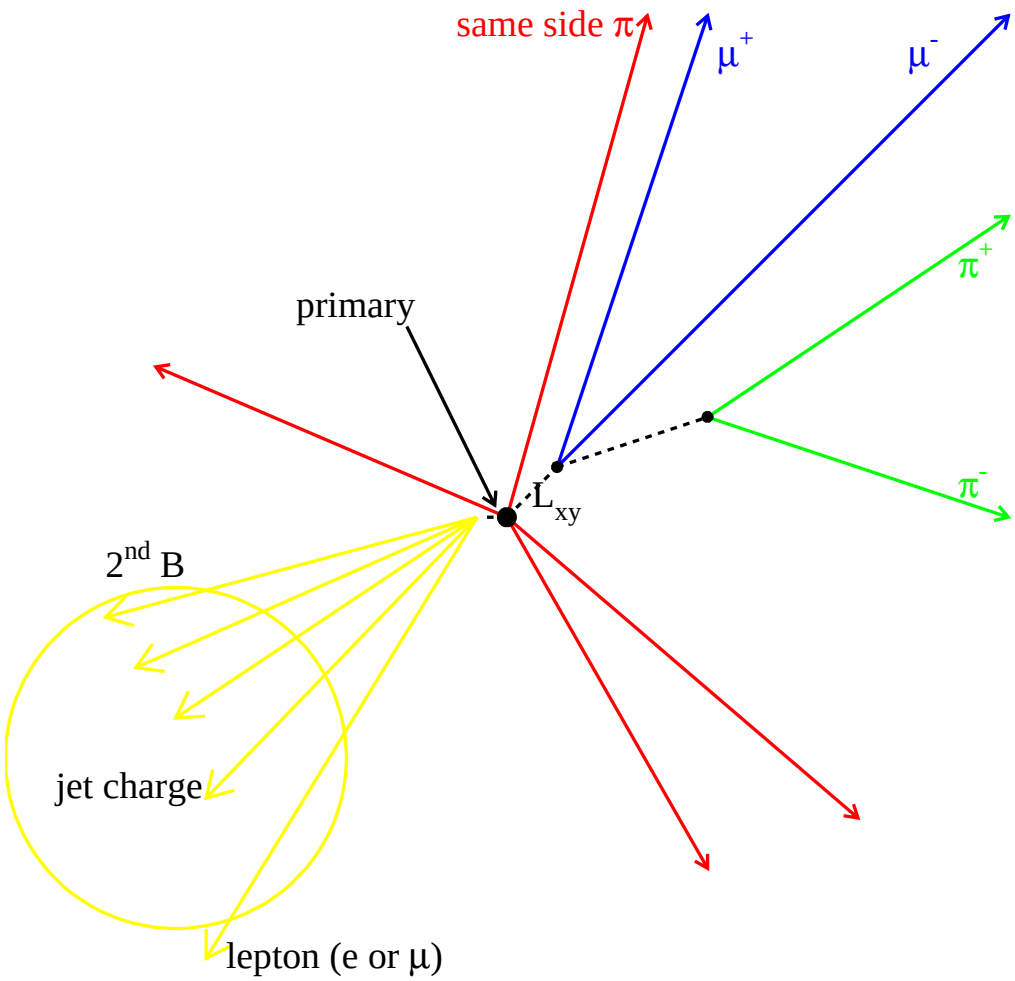
**Yield =** $(2 \times 10^{10}\text{quarks}) \cdot (2 \times 10^{-8}) = 400$ **events**

**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 $\mu$ 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:**

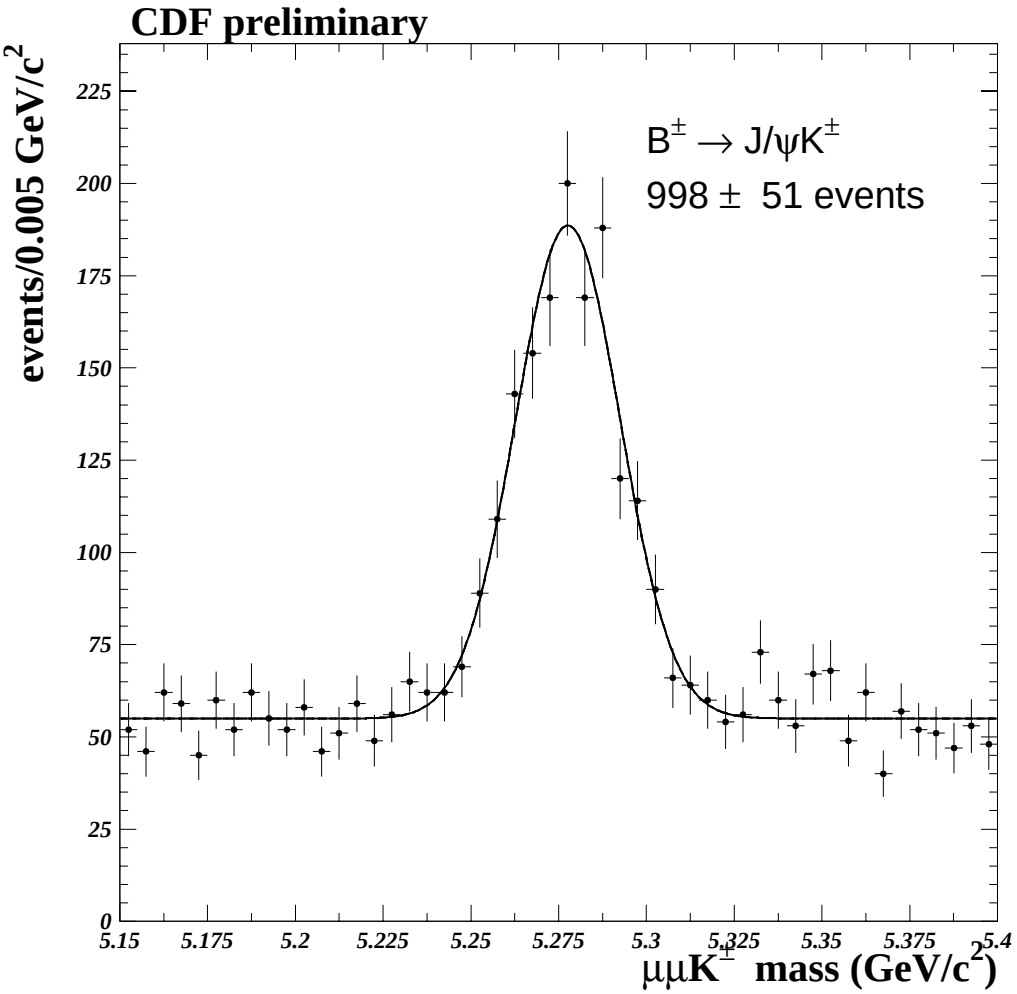
- $b \to \overline{B^0} \to J/\psi K^0_S$
- $\bar{b} \to B_2$ **($B_2 = B^0, B^+, B^0_s$,etc.)**

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

- **Soft Lepton Tagging (SLT)**
  - $\to$ **looking for $B_2 \to \ell + X$**
  - $\to$ **$\ell$ = electrons and muons**
  - $\to$ **very high dilution, very low efficiency**
- **Jet Charge Tagging (JetQ)**
  - $\to$ **looking for $B_2 \to X$**
  - $\to$ **find a "jet" of charge tracks**
  - $\to$ **momentum weighted charge sum $\Rightarrow$ correlated with $B$ or $\bar{B}$**
  - $\to$ **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:**

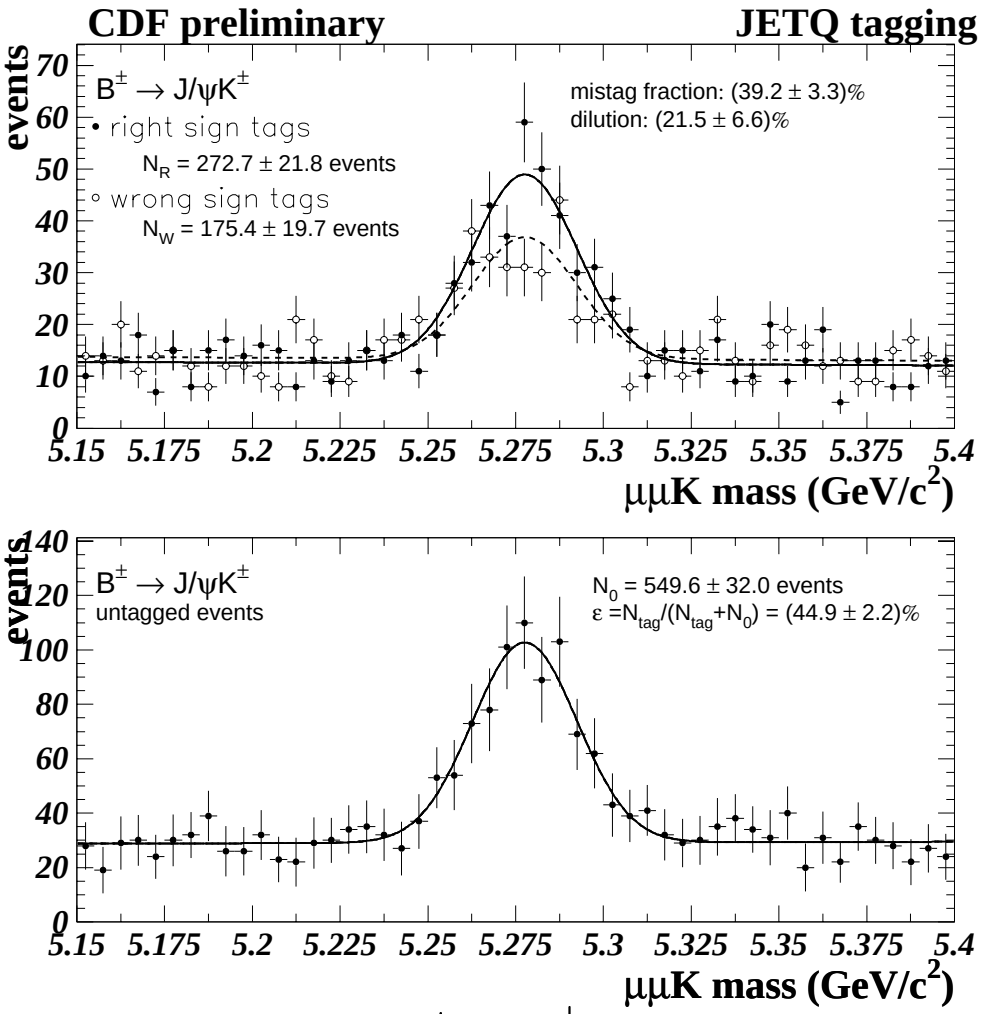



- **since we are fully reconstructing a charged $B$ decay, we already know the answer**

  **(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:** $w = (39.2 \pm 3.3)\%$

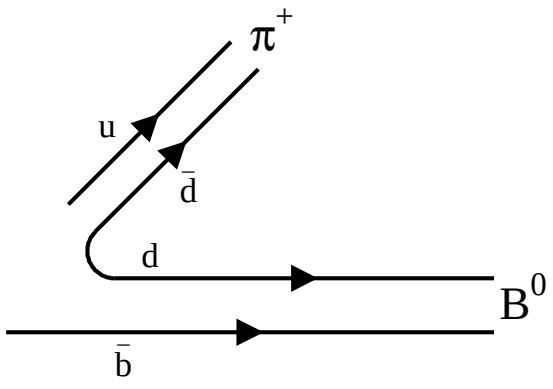
# "Same-side" Tagging

**Problems with opposite-side tagging:**

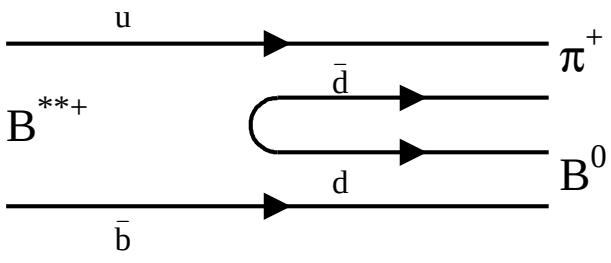
- **opposite $b$-hadron is central (within detector acceptance) only $50\%$ of the time**
- **if opposite $b$-hadron is $B^0$ or $B_s$, mixing degrades ability to tag**

**Same Side Tagging (SST):**

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




fragmentation




via $B^{**}$

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

# Summary of Flavor Tagging Algorithms

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

$^\dagger$ an SLT tag overrides jet-charge

**The tagging algorithms all have similar power:**

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

**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**
- **$\epsilon_+$: the tagging efficiency for (+) tags**
- **$\epsilon_-$: the tagging efficiency for (-) tags**

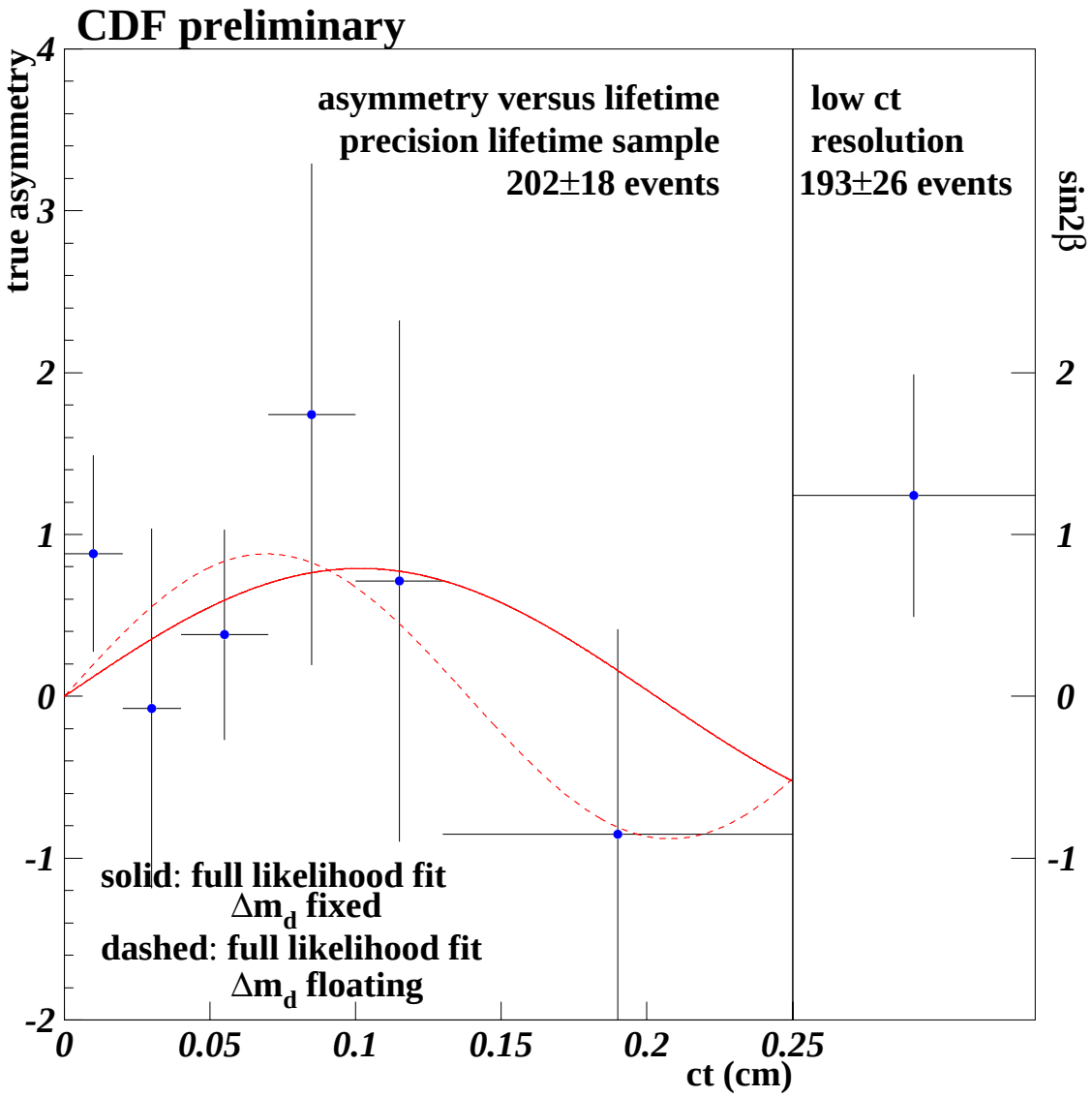
# Outline

1. **Introduction:**
   - **Charged Current Decays**
   - **the CKM Matrix**
   - $B/\overline{B}$ **Mixing**
2. $CP$ **violation**
   - **Introduction**
   - **the** $J/\psi K^0_S$ **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**

# Results

## We measure:

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




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

# Systematic Uncertainties

**Specifically splitting off the systematic error, we find:**

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

**Summary of systematic error evaluation:**

| parameter | evaluated | $\delta \sin 2\beta$ |
|---|---|---|
| tagging dilution | in fit | 0.16 |
| tagging efficiency | in fit | |
| $\Delta m_d$ | in fit | 0.01 |
| $\tau_{B^0}$ | in fit | 0.01 |
| $m_B$ | refit | 0.01 |
| trigger bias | external | negligible |
| $K^0_L$ regeneration | external | negligible |

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

## Float $\Delta m_d$

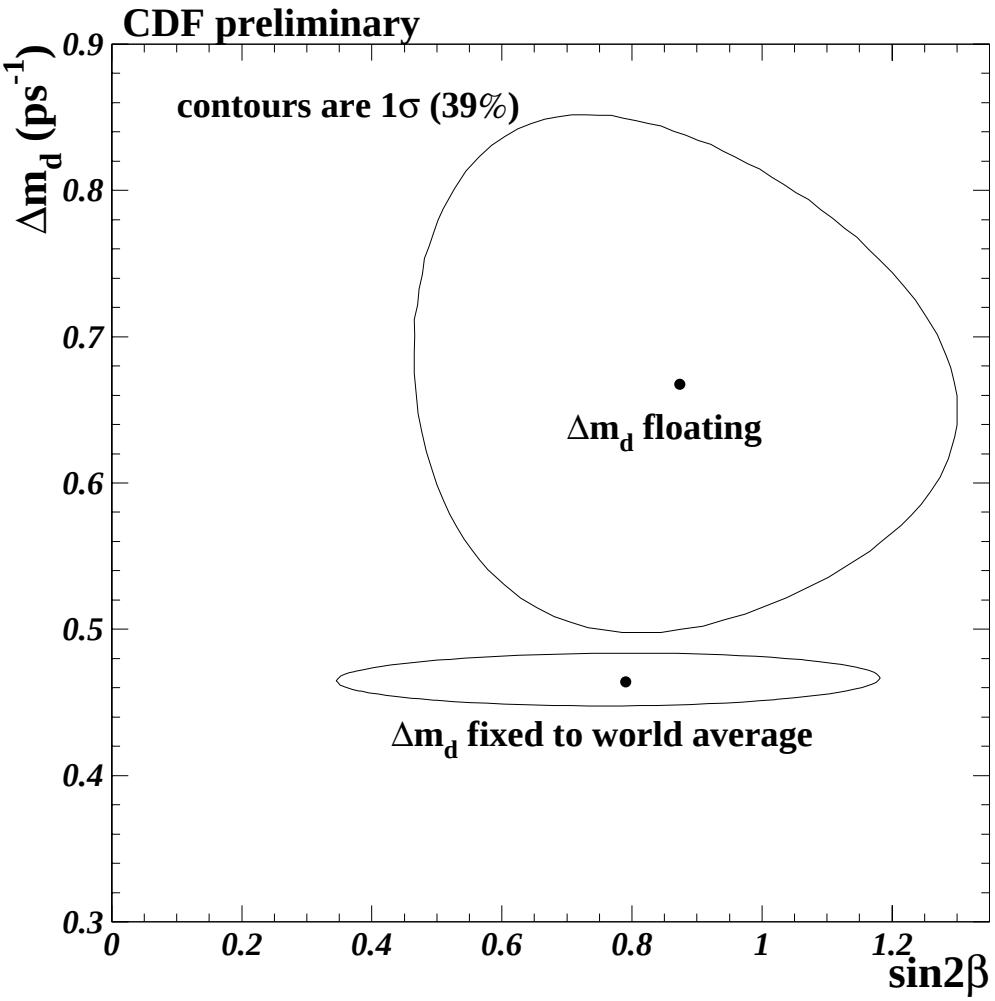
**When we let $\Delta m_d$ float in the fit, we measure:**

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

**and**

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

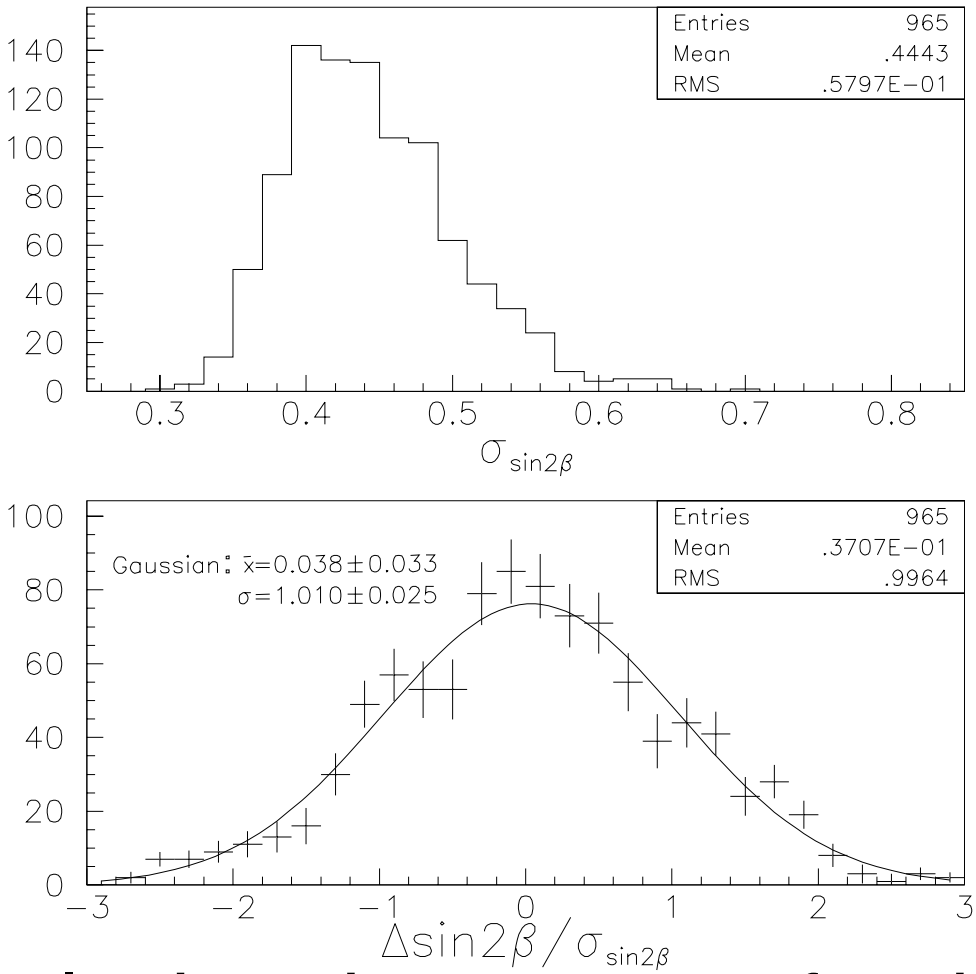
**The $1\sigma$ contour:**




**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.**

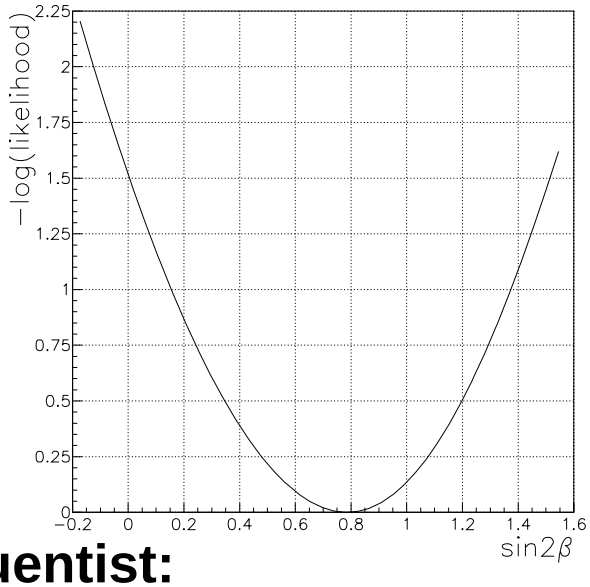
# Limits

**We measure:**

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

**(Note: this result is with $\Delta m_d$ 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 $0.79 \rightarrow \infty$:**

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

# Direct Measurements

- **OPAL (January '98)**

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

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

  $\rightarrow$ **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

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

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

- **ALEPH (November '99)**

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

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

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

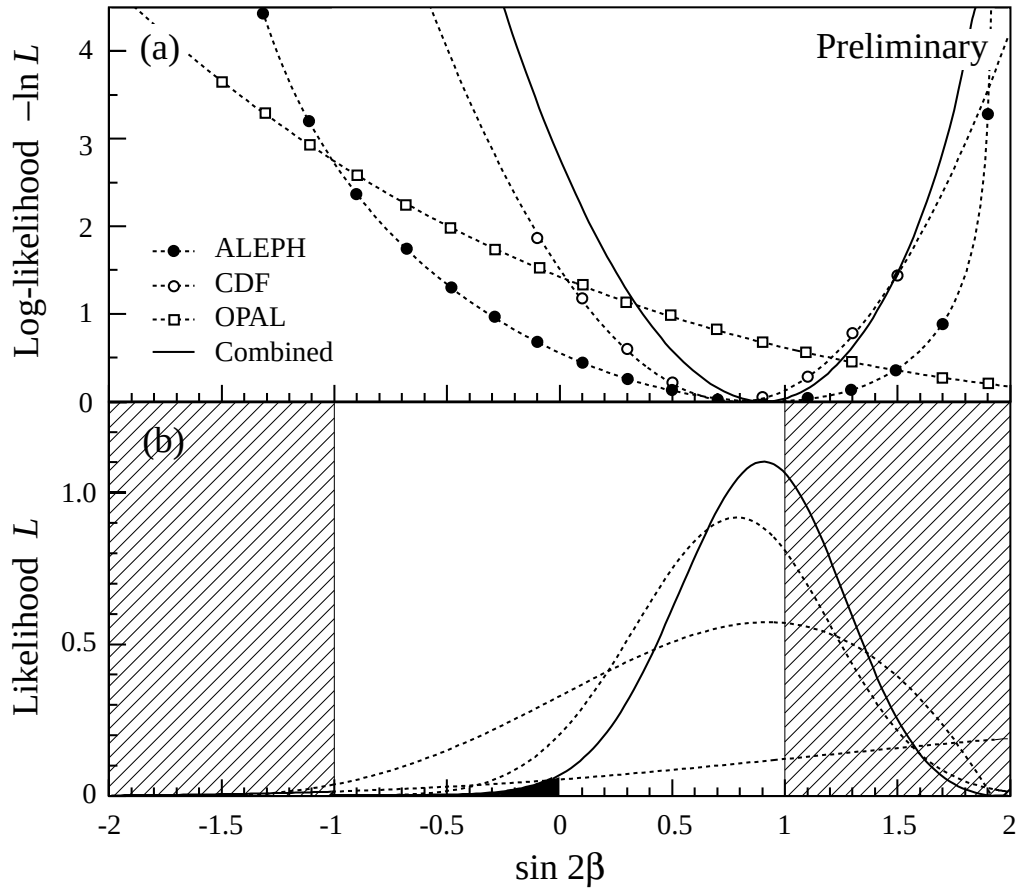
**LEP measurements have much fewer events, but are able to do much better flavor tagging.**

**$B$ 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)**

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

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

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

**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 |
| $\delta(\sin 2\beta)$ | $\psi K^0_S$ | 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: $BR(B^0 \to \pi^+\pi^-) = (4.7^{+1.8}_{-1.5} \pm 0.6) \times 10^{-6}$

$^\dagger$ assuming that penguin contamination can be unfolded

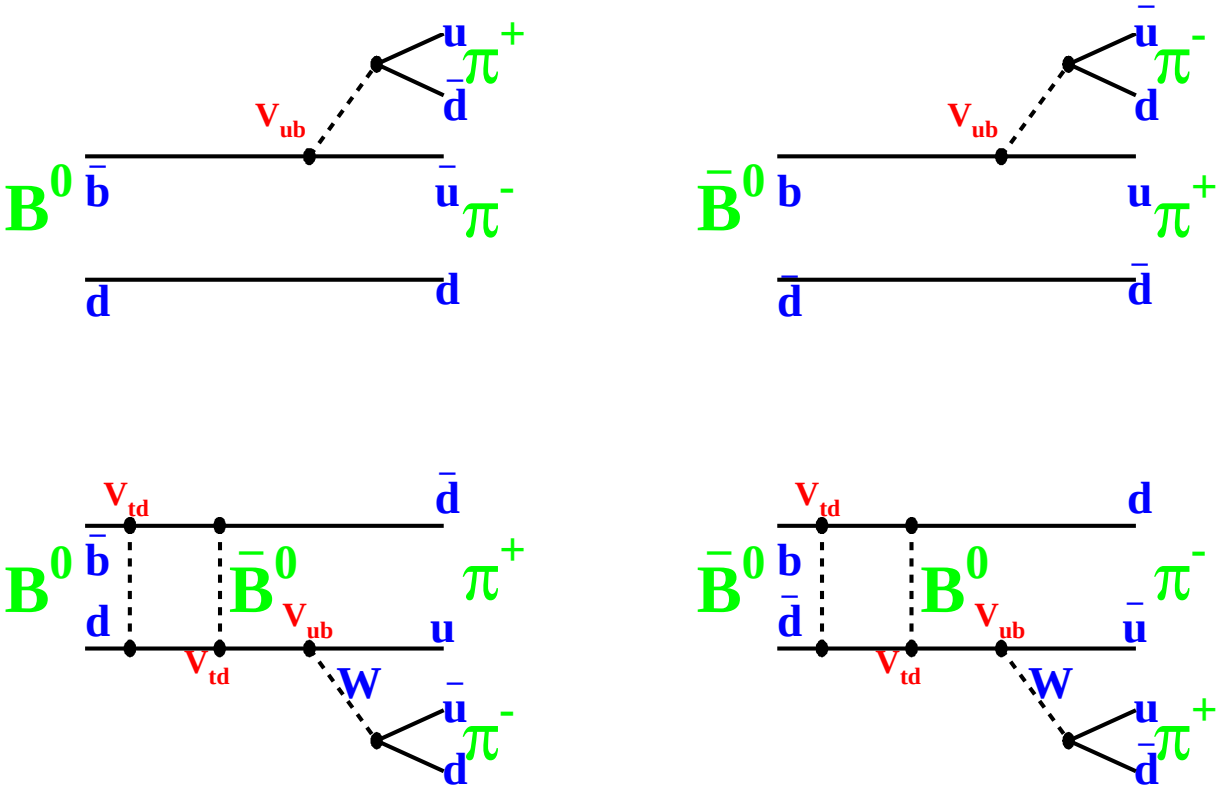
## An incomplete list for EVERY experiment.

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 $\beta$ coming from the mixing (just like the $J/\psi K^0_S$ final state.)**

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

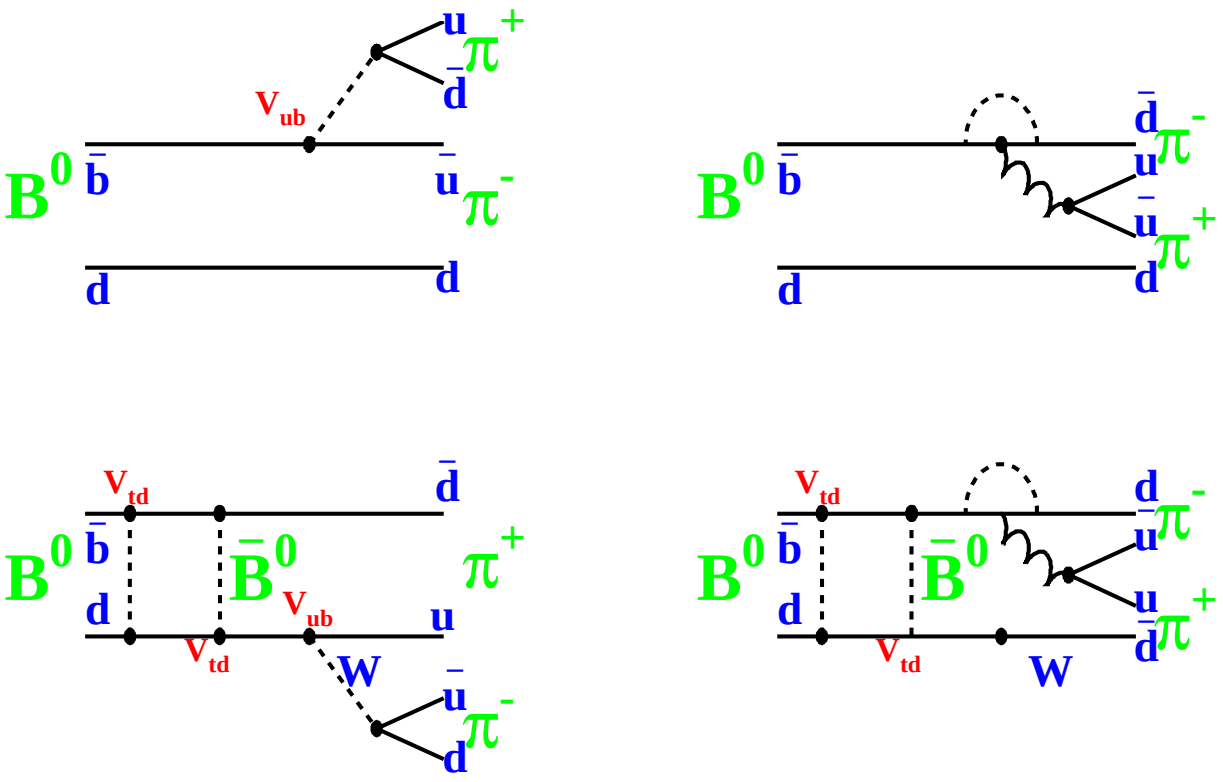
**Phase is then $\beta + \gamma$ and $CP$ asymmetry is proportional to:** $(\alpha + \beta + \gamma = \pi)$

$$\sin 2\alpha$$

**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** $\gamma$ **(difficult)**
- $\beta$ **and** $\alpha$ **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!**