CP Violation in B Decays from the Tevatron: Results and Prospects

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What This Talk Covers

Results on CP Violation in Run I

- August 1992 to February 1996
- CDF and D0 collected 100 pb^{-1} of data each
- Results on CP Violation from CDF only
- Main emphasis of this talk

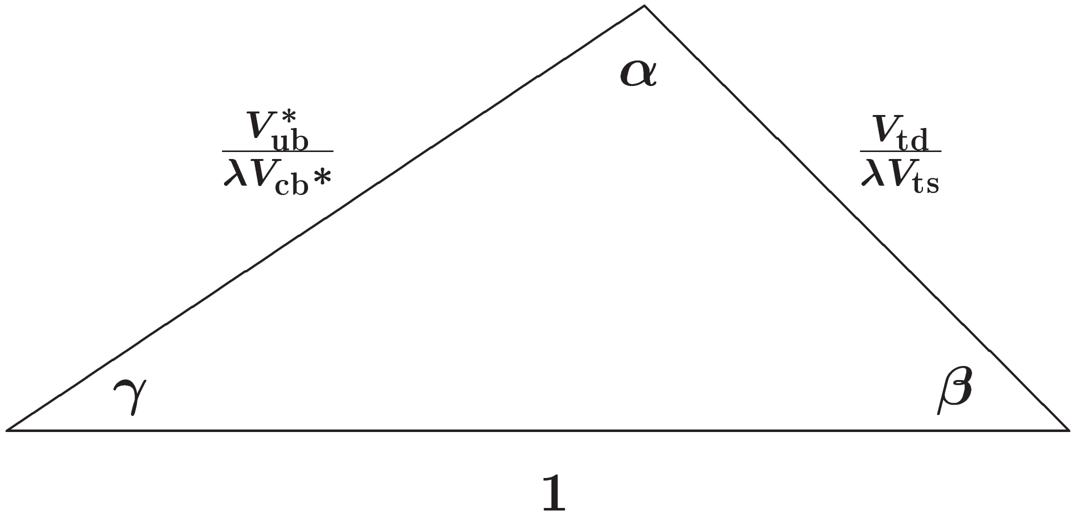
Prospects for CP Violation in Run II

- Begins in Spring 2000
- Initial Integrated $\mathcal{L} = 2$ fb^{-1}
  Expected in 2 years
- *i.e.*, 10^{11} $b\bar{b}$ per year
- Projections based on CDF Run I data

I do not discuss beyond Run II when FNAL may have a dedicated B physics detector

Future Analysis in B Physics

Goal of B physics in next decade:



Next test of Unitarity may be a combination of:

1. $\sin(2\beta)$ from $B^0/\bar{B}^0 \to J/\psi K_S^0$
2. $|V_{td}/\lambda V_{ts}|$ from $B^0 - \bar{B}^0$ and $B_s^0 - \bar{B}_s^0$ flavor oscillations

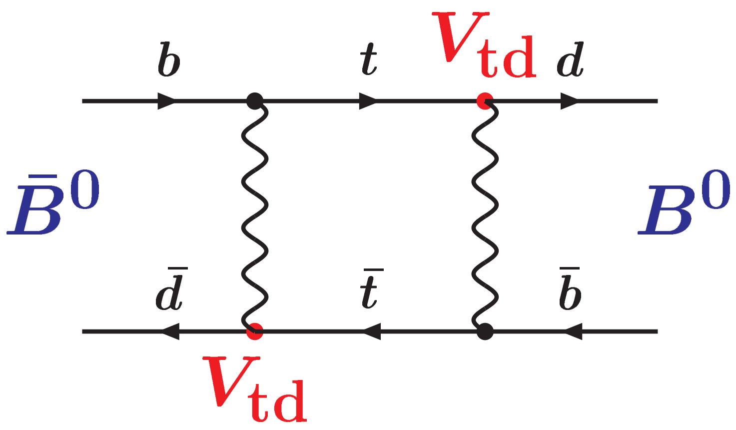
CDF/D0 are in the unique position to do both

CP Violation in B Decays

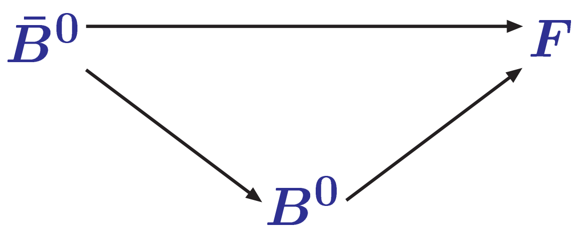
Cleanest measurements use

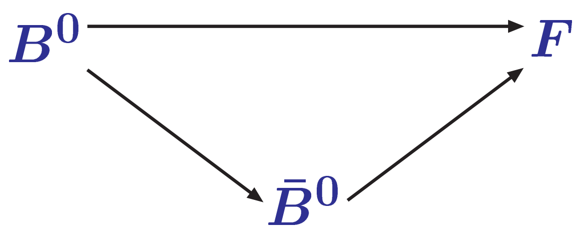
$$B^0/\bar{B}^0 \to F, \text{ where } CP|F\rangle = \pm|F\rangle$$

CP Violation induced by mixing



V_{td} puts complex phase in Weak Amplitude





Two paths (amplitudes) to F interfere

$$\boxed{\Gamma(B^0 \to F) \neq \Gamma(\bar{B}^0 \to F)}$$

Golden Mode: $B^0/\bar{B}^0 \to J/\psi\, K^0_S$

CLEAN: Asymmetry directly related to $\sin 2\beta$

$$\mathcal{A}_{CP} = \frac{N(\bar{B}^0 \to J/\psi\, K^0_S) - N(B^0 \to J/\psi\, K^0_S)}{N(\bar{B}^0 \to J/\psi\, K^0_S) + N(B^0 \to J/\psi\, K^0_S)}$$

UNLIKE $\Upsilon(4S)$ time integrated $\mathcal{A}_{CP}$ nonvanishing at hadron collider

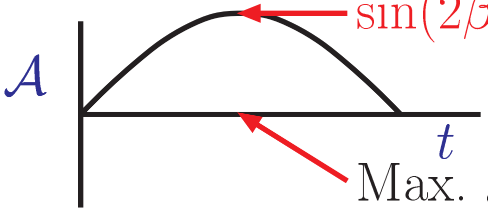
$$\mathcal{A}_{CP} = \frac{x_d}{1+x_d^2}\sin 2\beta \approx 0.5 \sin 2\beta$$

Lucky! $x_d = 0.732 \pm 0.032$ (PDG98)

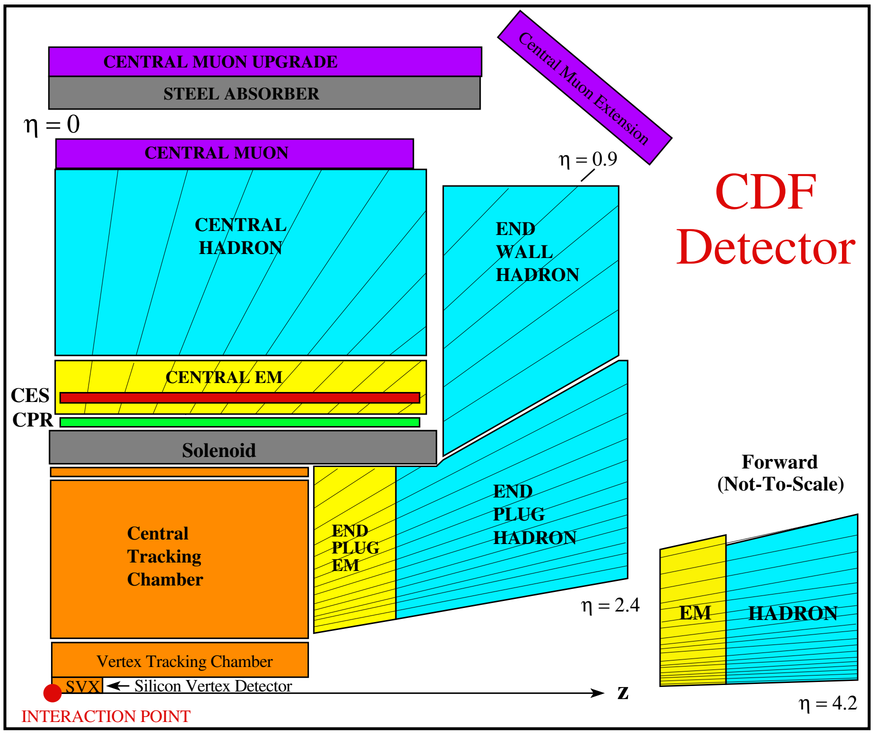
BUT better to measure proper time dependence of $\mathcal{A}_{CP}(t)$

$$\mathcal{A}_{CP}(t) = \sin 2\beta \sin(\Delta m_d t)$$

- More statistical power
  Signal at small t dilutes $\mathcal{A}_{CP}$
- Decreases effect of background
  Most combinatoric background at small t



The Run I CDF Detector



Features crucial for B Physics

- Silicon Microstrip Detector **(lifetimes)**

  Impact parameter: $\sigma_{d_0} = (13 + 40/p_T)\,\mu\text{m}$

- Central Tracking Chamber **(mass resolution)**

  B Field $= 1.4\,\text{Tesla}$; Radius $r = 1.4\,\text{m}$

  $(\delta p_T/p_T)^2 = (0.0066)^2 \oplus (0.0009 p_T)^2$

- Lepton Detection: $(b \to \ell,\ J/\psi \to \mu^+\mu^-)$

  Central e: $|\eta| < 1$

  Central μ: $|\eta| < 1.0$; Forward μ: $2.0 < |\eta| < 2.6$

Overview of Analysis (1)

Measure asymmetry $\mathcal{A}_{CP}(t)$:

$$\mathcal{A}_{CP}(t) = \frac{\frac{dN}{dt}(\bar{B}^0 \to J/\psi\, K^0_{\mathrm{S}}) - \frac{dN}{dt}(B^0 \to J/\psi\, K^0_{\mathrm{S}})}{\frac{dN}{dt}(\bar{B}^0 \to J/\psi\, K^0_{\mathrm{S}}) + \frac{dN}{dt}(B^0 \to J/\psi\, K^0_{\mathrm{S}})}$$

$$\mathcal{A}_{CP}(t) = \sin(2\beta)\sin(\Delta m_d t)$$

To accomplish this we must:

1. Reconstruct signal $B^0/\bar{B}^0 \to J/\psi\, K^0_{\mathrm{S}}$
2. Measure proper decay time t
3. Flavor tag: Produced B^0 ($\bar{b}d$) or $\bar{B}^0$ ($b\bar{d}$)?

B^0-$\bar{B}^0$ flavor oscillations (Δm_d) also need tag

$\Longrightarrow$ use these measurements to understand tags

Quantify tags with efficiency ϵ and Dilution D

$\epsilon =$ fraction of candidates with tag

$D = 2 \cdot \mathcal{P} - 1$ ($\mathcal{P} =$ prob. of correct tag)

Overall tag effectiveness: ϵD^2

Overview of Analysis (2)

Amplitude of CP asymmetry reduced by D:

$$\mathcal{A}_{CP}^{\text{meas}}(t) = D\sin(2\beta)\sin(\Delta m_d t)$$

Error on $\mathcal{A}$ depends on ϵD^2:

$$\delta\mathcal{A} = \sqrt{\frac{1 - D^2\mathcal{A}^2}{\epsilon D^2 N}}$$

To measure B^0-$\bar{B}^0$ flavor oscillations:

$$\mathcal{A}(t) = \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)} = D \cdot \cos(\Delta m t)$$

Flavor osc. amplitude also reduced by D

Use mixing to determine ϵ and D

Note: $\epsilon D^2 \sim 1\%$ or larger is respectable

Methods of b Flavor Tagging

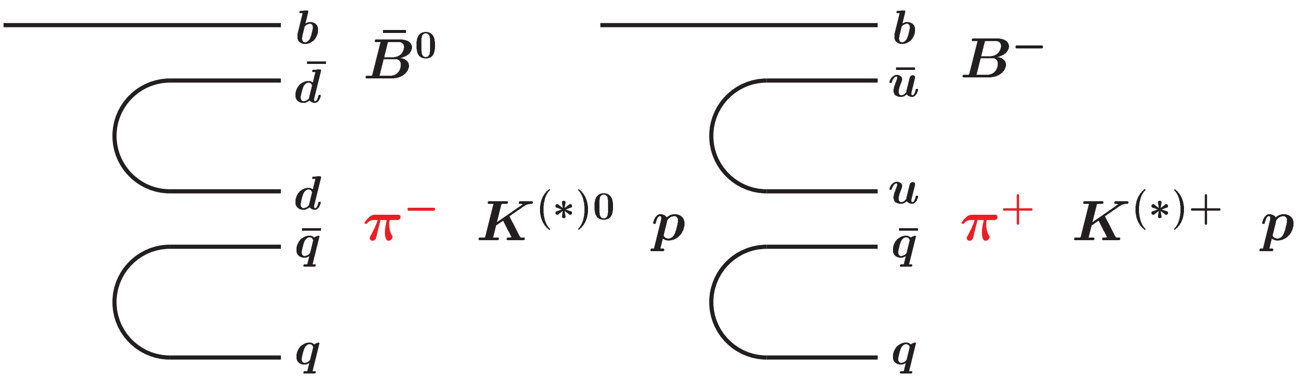
1. Opposite-side flavor tags (OST)

Identify flavor of other B in event
infer flavor of B decay of interest

- lepton tag: $b \to \ell^- X$, but $\bar{b} \to \ell^+ X$
- jet-charge tag: $Q^b_{\rm jet} < 0$, but $Q^{\bar{b}}_{\rm jet} > 0$
- $\sim 40\%$ acceptance of other B

2. Same-side flavor tag (SST)

Exploit correlation:
b-flavor and fragmentation particle charge
(also B^{**})

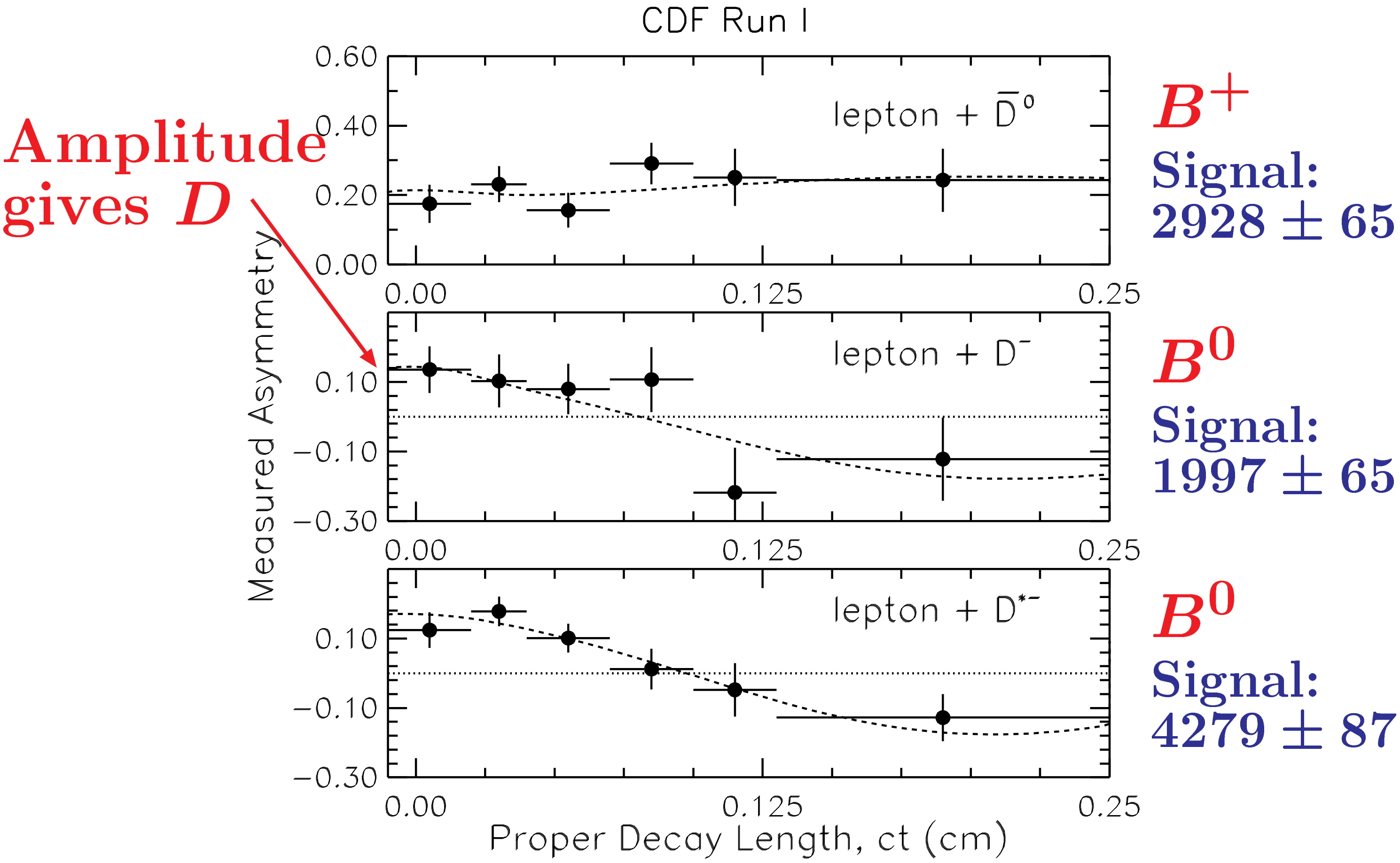


i.e., π^+ tags a B^0 and π^- tags a $\bar{B}^0$

Better acceptance (efficiency) than OST

Example: SST and $\bar{B}^0 \to \ell^- D^{(*)+} X$

CDF Collaboration, F. Abe *et. al.*, Phys. Rev. Lett. **80**, 2057 (1998) and Phys. Rev. D **59**, 032001 (1999).



Measure efficiency ϵ and dilution D of tag:

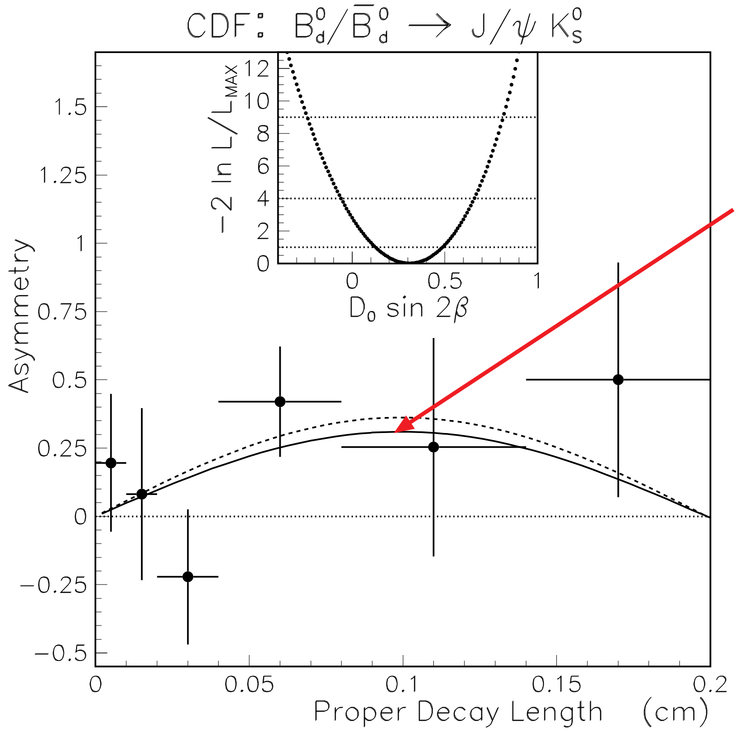
Find $\epsilon D^2 = (2.4 \pm 0.7^{+0.6}_{-0.4})\%$ for B^0

First Measurement of $\sin(2\beta)$

CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **81**, 5513 (1998)

Signal: 198 ± 17 $B^0/\bar{B}^0 \to J/\psi K^0_S$

Measure raw asymmetry with Same-side tag



$D \cdot \sin(2\beta) =$
0.31 ± 0.18 (stat)
± 0.03 (syst)
(Main syst. are Δm_d and det. biases)

Using $D = 0.166 \pm 0.018(\text{data}) \pm 0.013(\text{MC})$

Find $\sin(2\beta) = 1.8 \pm 1.1$ (stat) ± 0.3 (syst)
(Syst. includes dilution uncertainty)

Preliminary Update of $\sin(2\beta)$

Improve statistical power of published result

1. Add candidates not fully reconstructed in silicon vertex detector (SVX)
   - doubles signal to ≈ 400
   - additional signal has larger $\sigma(t)$
2. Add two additional flavor tags: soft-lepton and jet-charge
   - both are opposite-side tags
   - used in B^0 mixing analysis
   - calibrated using data: $B^- \to J/\psi K^-$

Multiple flavor tags $\Longrightarrow$ use maximum $\mathcal{L}$

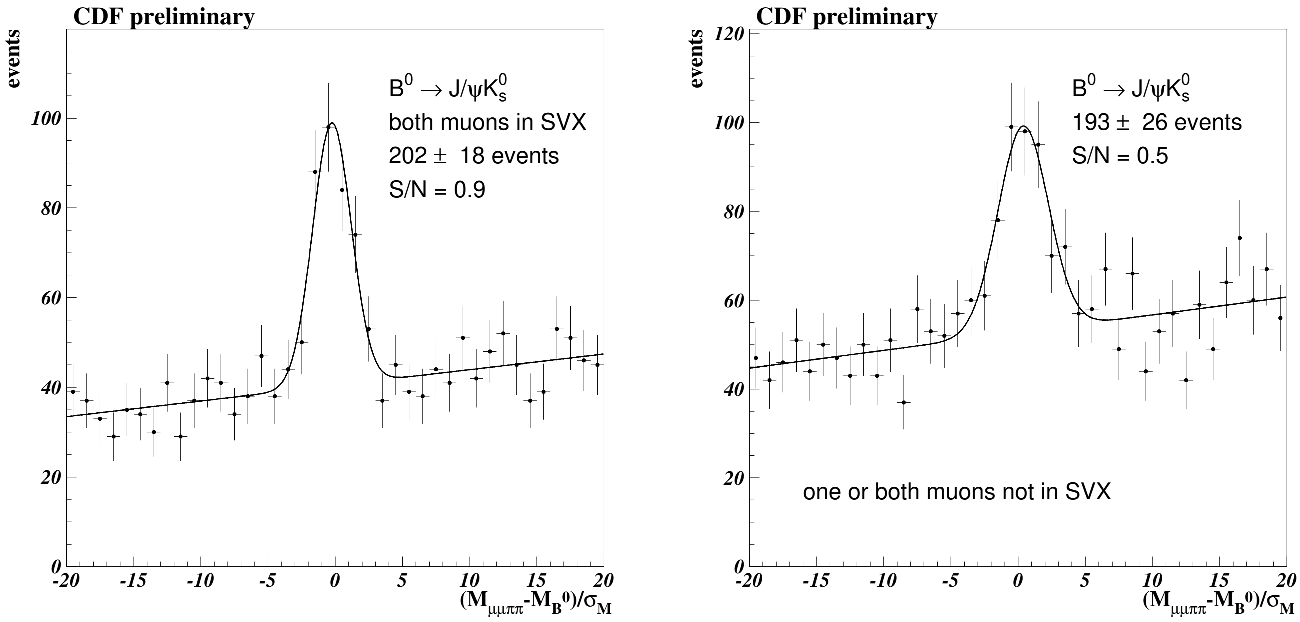
Include terms in likelihood for

- Possible detector biases
- prompt background: $p\bar{p} \to J/\psi X$ + random K^0_S
- long-lived background: $B \to J/\psi X$ + random K^0_S

Signal: $B^0/\bar{B}^0 \to J/\psi\, K^0_S$

Add candidates not fully contained in SVX

- Candidates in SVX: $\sigma(t) \sim 60\mu\mathrm{m}$
- Not in SVX: $\sigma(t) \sim (300 - 900)\mu\mathrm{m}$



Plots are normalized mass:

$$\frac{(M(J/\psi K^0_S) - M(B^0))}{\sigma(M)}$$

Mass resolution:

$$\sigma(M) \sim 10\,\mathrm{MeV}/c^2$$

Total signal: 395 ± 31

Add Opposite-side Flavor Tags

Add two flavor tags used in mixing analysis

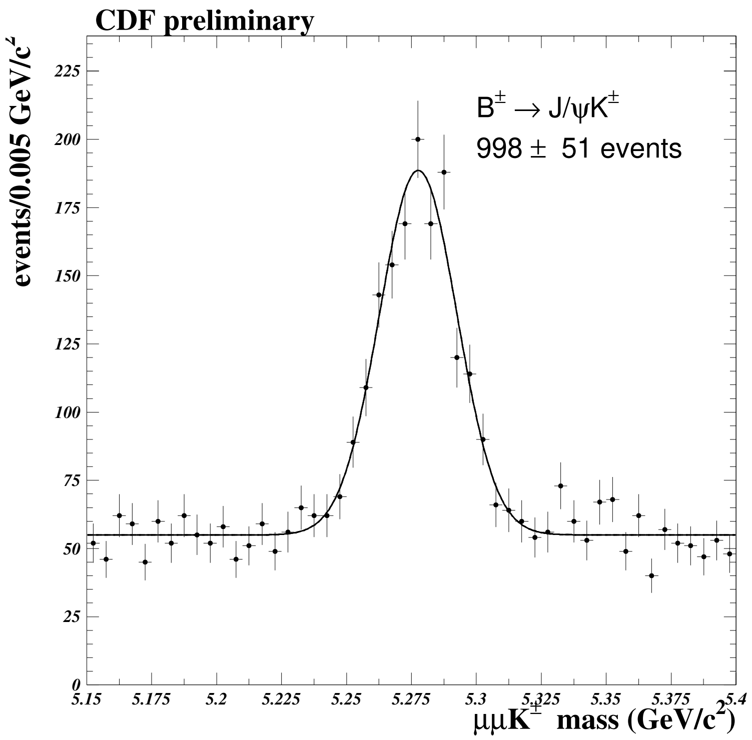
(F. Abe *et al.*, FERMILAB–PUB–99/019–E, hep-ex/9903011)

Soft Lepton: identical algorithm

$e: \quad p_T > 1\,\mathrm{GeV}/c$; $\mu: \quad p_T > 2\,\mathrm{GeV}/c$

Jet Charge: modified to increase efficiency

Calibrate with $B^{\pm} \to J/\psi K^{\pm}$ Signal: 998 ± 51



Same kinematics as signal sample

Summary of Flavor Tag Performance

1. **Soft Lepton:**

   $e: \quad p_T > 1\,\mathrm{GeV}/c$; $\mu: \quad p_T > 2\,\mathrm{GeV}/c$

   $\epsilon = (6.5 \pm 1.0)\%$

   $D = (62.5 \pm 14.6)\%$

   $\epsilon D^2 = (2.2 \pm 1.0)\%$

2. **Jet Charge:**

   IF soft lepton, do not use Jet Charge

   $\epsilon = (44.9 \pm 2.2)\%$

   $D = (21.5 \pm 6.6)\%$

   $\epsilon D^2 = (2.2 \pm 1.3)\%$

3. **Same side pion:**

   $\epsilon \approx 70\%$

   $D = (16.6 \pm 2.2)\%$ in SVX

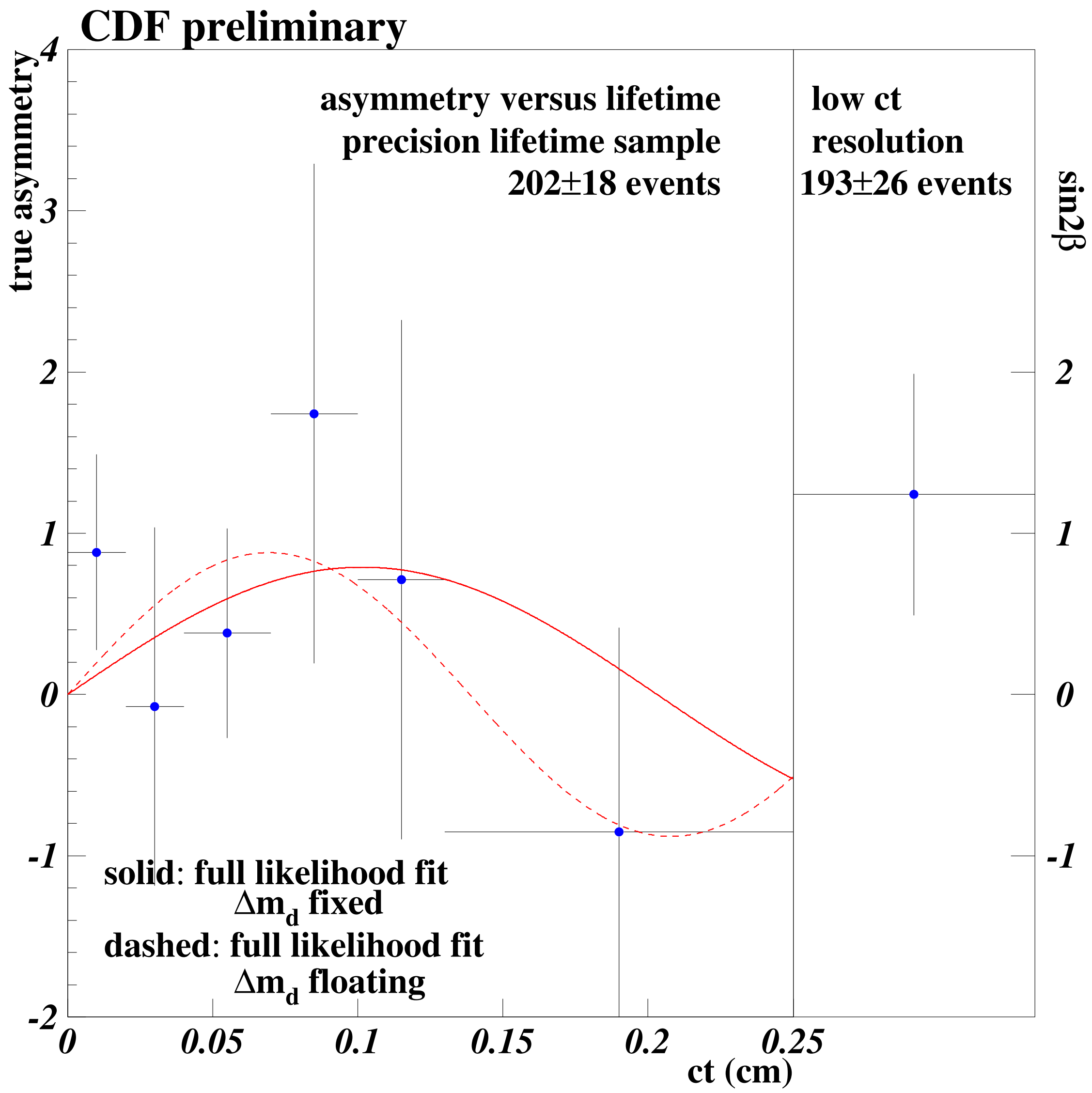
   $D = (17.4 \pm 3.6)\%$ not in SVX

   $\epsilon D^2 = (2.1 \pm 0.5)\%$

Combined Tagging efficiency

$$\epsilon D^2 = (6.3 \pm 1.7)\%$$

Preliminary Update of $\sin(2\beta)$



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

$$(\text{Time integrated: } \sin 2\beta = 0.71 \pm 0.63)$$

Systematics: $\sin(2\beta)$

Dominated by determination of Dilution from statistics of calibration sample

Source	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

Let Δm_d float in fit

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

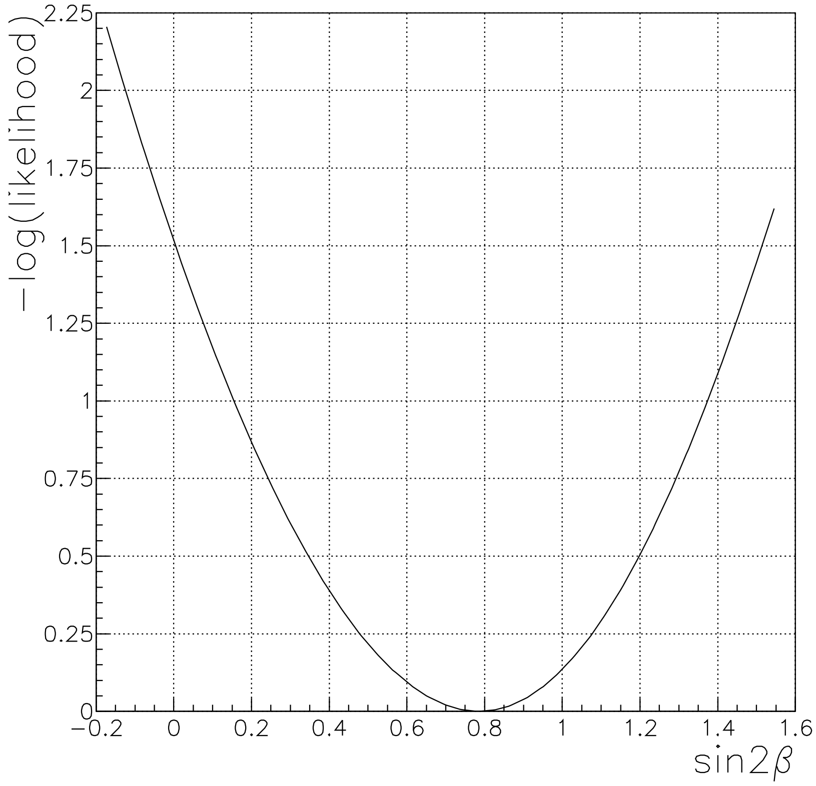
$$\Delta m_d = 0.68 \pm 0.17\,\mathrm{ps}^{-1}$$

Statistical error from $J/\psi K_S^0$ sample size and tagging ϵD^2 (0.39) larger than systematics

This will continue to be the case in Run II: Signal and Calibration samples both increase

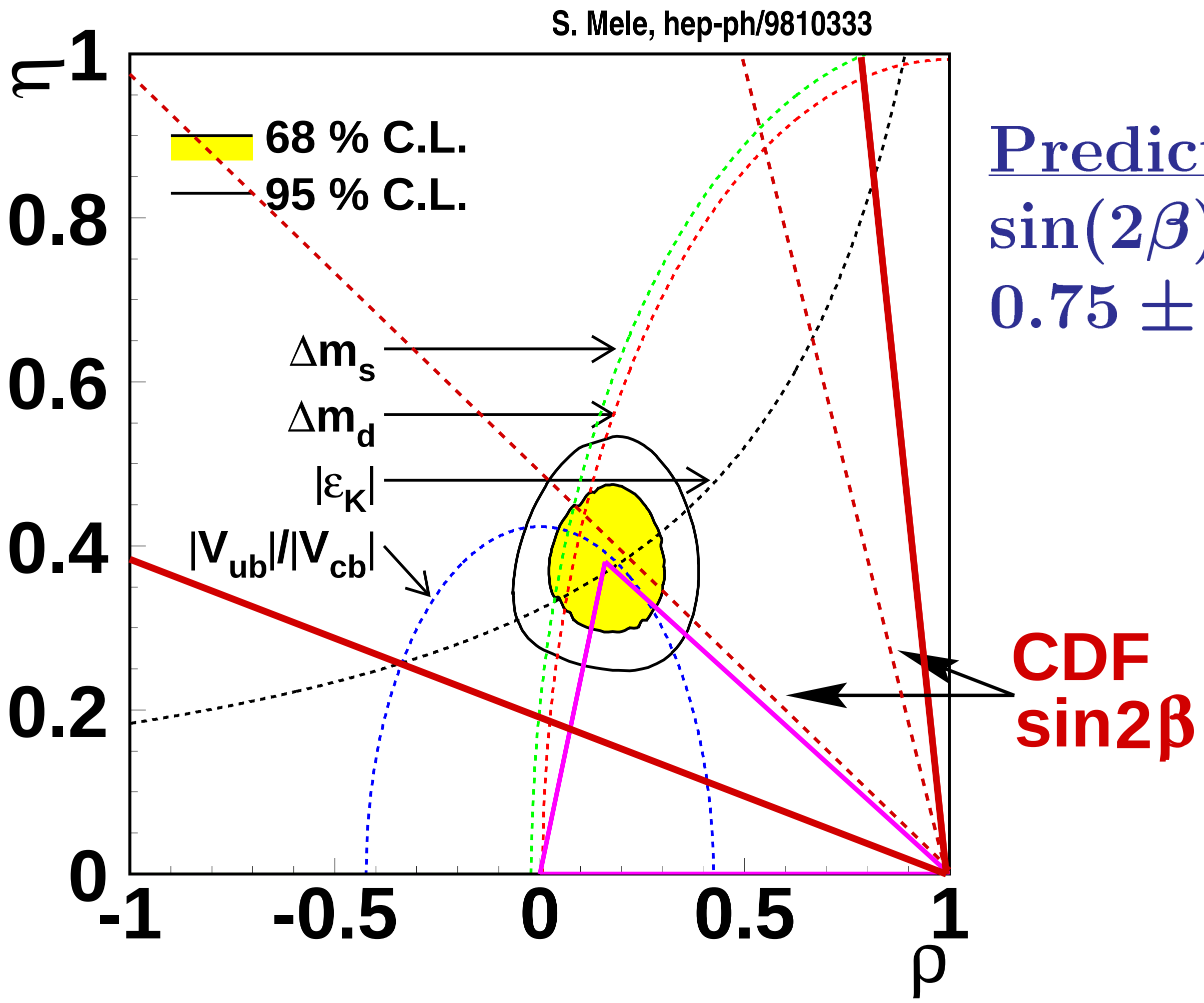
Confidence Limits on sin(2β)

Uncertainties $\sim$ Gaussian



- **Feldman-Cousins (Frequentist):**
  $0 < \sin 2\beta < 1$ at 93% C.L.
- **Bayesian (prior flat in $\sin 2\beta$):**
  $0 < \sin 2\beta < 1$ at 95%
- **If true value $\sin 2\beta = 0$ probability of observing $\sin 2\beta > 0.79$ is 3.6%**

Limit in $\rho - \eta$ Plane



Predicts:
$\sin(2\beta) =$
0.75 ± 0.09

- Fourfold ambiguity: two not shown
- Solid lines are the 1σ bounds
- Dashed lines are two solutions for β

CDF Upgrade for Run II

New silicon tracking system

- SVX II: 5 Layer, 96 cm, $r-\phi$ and $r-z$
- ISL: 2 additional layers, covers $|\eta| < 2$

3D Vertex, $\sim$ 2 more acceptance

New central drift chamber

Maintain Run I track eff. and resol.

New deadtimeless trigger

- Track trigger moved to Level 1
- Use silicon information at Level 2

Purely hadronic B trigger possible

Recently approved additions

- New inner layer of Si at $r = 1.4\,\mathrm{cm}$
- Time-of-Flight:
  2σ K/π sep. for $p < 1.6\,\mathrm{GeV}/c$

D0 Upgrade for Run II

Superconducting Solenoid (B = 2 Tesla)

Central Fiber Tracker

- 8 superlayers of scintillating fibers
- full coverage in $|\eta| < 1.7$

Charged particle momentum measurement

Silicon Microstrip Tracker

- 6 barrels, each 4 layers, with $r - \phi$ and $r - z$
- 16 disks out to $|z| < 1.2\,\mathrm{m}$

Tag B decays with displaced vertices

With improvements to muon system and trigger, and existing calorimeter, will be competitive for B physics

Tevatron Run II B Physics

- Precise Measurement of $|V_{\rm td}/V_{\rm ts}|$
  - (†) B_s^0–$\bar{B}_s^0$ flavor oscillations (also $\Delta\Gamma_s/\Gamma_s$)
  - Radiative decays:
    e. g. $B_s^0 \to K^{*0}\gamma$ vs. $B_s^0 \to \phi\gamma$ (†)
- Observe CP Violation in $B^0/\bar{B}^0 \to J/\psi K_{\rm S}^0$
  Precise measurement of $\sin(2\beta)$
- Observe CP Violation in $B^0/\bar{B}^0 \to \pi^+\pi^-$
  Precise measurement of asymmetry
  (related to $\sin(2\alpha)$)
- (†) Search for large CP Violation in
  $B_s^0/\bar{B}_s^0 \to J/\psi\,\phi$
  Unambiguous signal of physics beyond SM
- Observe decay modes related to angle γ:
  $B_s^0 \to D_s^{\pm}K^{\mp}$(†) and $B^+ \to \bar{D}^0 K^+$
- Observe $B^+ \to \mu^+\mu^- K^+$, $B^0 \to \mu^+\mu^- K^{*0}$,
  $B_s^0 \to \mu^+\mu^-\phi$ (†)
- (†) Study B_c^+ meson and b baryons

(†) Unique to Tevatron

Expectations for $\sin 2\beta$ and Δm_s

From CDF: similar expectations for D0
Based on projections using Run I Data

CP Asymmetry $\sin 2\beta$

- For 10K $B^0/\bar{B}^0 \to J/\psi K^0_S$
- Calibrate tags with 40K $B^\pm \to J/\psi K^\pm$ and 20K $B^0 \to J/\psi K^{*0}$
- $\epsilon D^2 = 6.7\%$ (add 2.4% more with TOF)

$$\delta(\sin 2\beta) \approx 0.084$$

$B^0_s - \bar{B}^0_s$ Flavor Oscillations

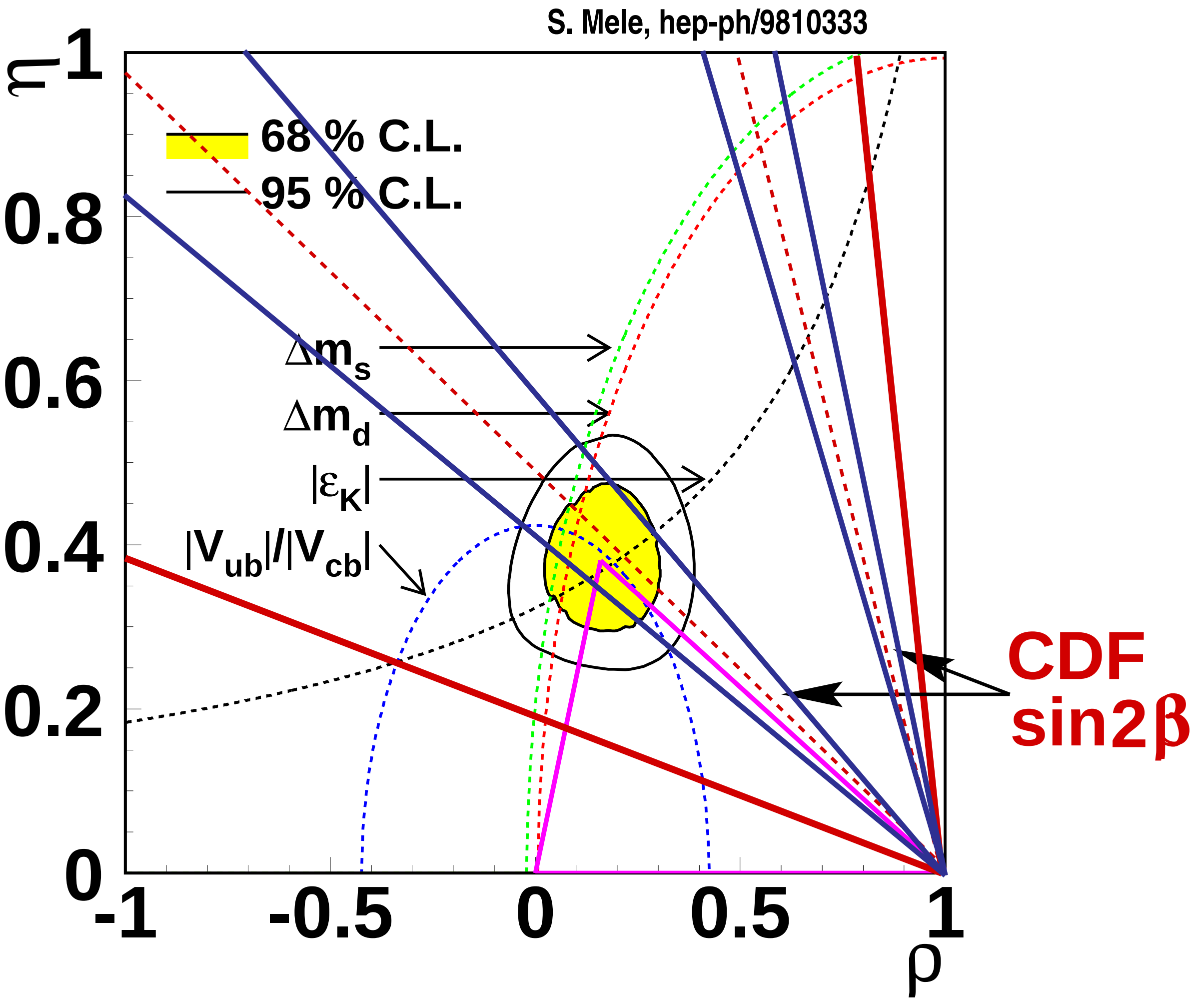
- Additional layer of Si improves $\sigma(t)$
  important if Δm_s unexpectedly large
- TOF doubles B^0_s ϵD^2 (Same-side K tag)
  Doubles statistical power of sample
- For 20K $\bar{B}^0_s \to D^+_s\pi^-, D^+_s\pi^-\pi^+\pi^-$
  (expect 5K to 30K from hadronic trigger)

Better than 5σ measurement for $\Delta m_s < 40$

Run II: Expected Limit in $\rho - \eta$ Plane

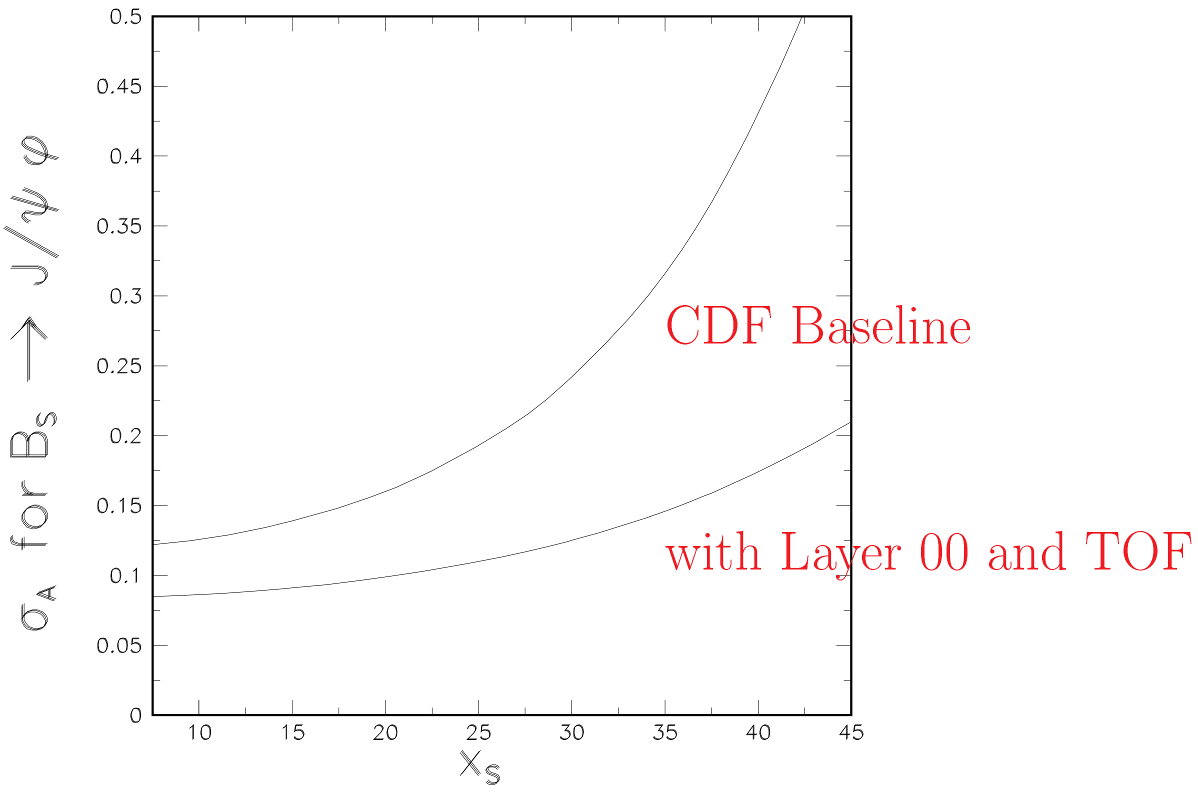
Run I value with proj. Run II error:

$$\sin(2\beta) = 0.79 \pm 0.084$$



CP **Violation in** $B_s^0/\bar{B}_s^0 \to J/\psi\phi$

- Small in the Standard Model
  Significant asymmetry unambiguous sign of new physics
- Expected signal: 6000 $B_s^0/\bar{B}_s^0 \to J/\psi\phi$
- Requires measurement of x_s
- Expected combined ϵD^2 for this sample: $\epsilon D^2 = 9.7\%$



Other CP Modes in Run II

Using displaced track trigger

$\sin(2\alpha)$

- $B^0/\bar{B}^0 \to \pi^+\pi^-$

  Signal: 8 400 to 15 200

  (assumes BR$= 1.0 \times 10^{-5}$)

  $\delta\mathcal{A}(\pi^+\pi^-) \sim 0.09$ for $\epsilon D^2 = 9.1\%$

$\sin(\gamma)$

- $B_s^0/\bar{B}_s^0 \to D_s^\pm K^\mp$

  Signal: ~ 700

- $B^\pm \to K^\pm D_{CP}^0$
- $B^- \to K^- D^0, D^0 \to K^+\pi^-$ and
  $B^- \to K^- \bar{D}^0, \bar{D}^0 \to K^+\pi^-$

Summary

Run I:

Important measurements of B hadron decay properties despite trigger restrictions.

Competitive with e^+e^- colliders.

Gained experience ($\sin 2\beta$) and developed tools (*e.g.*, flavor tags and trigger strategies) for Run II.

$\sin 2\beta = 0.79^{+0.41}_{-0.44}$ (preliminary)

Run II:

Improved detectors increase scope of B Physics: *e.g.*, hadronic B triggers and TOF for PID.

Precision on $\sin 2\beta$ competitive with B factories (and is complementary). CP asymmetries in B_s^0 decays and Δm_s unique to Tevatron.

The Tevatron will play a crucial, unique role in our test of the CKM Matrix.

B Physics at Hadron Colliders

Strong interaction produces b quarks

Examples of lowest order (α_s^2) production:

produces $b\bar{b}$ pairs close in y

Quarks fragment into hadrons

$\bar{B}^0$ $(b\bar{d})$, $\bar{B}_s^0$ $(b\bar{s})$, $\bar{B}^-$ $(b\bar{u})$, Λ_b (bdu), B_c^- $(b\bar{c})$

also B^*, B^{**} etc.

Lowest lying states decay via weak interaction

Studies of these decays leads to information on
$V_{\rm cb}$, $V_{\rm ub}$, $V_{\rm tb}$, $V_{\rm ts}$, $V_{\rm td}$
$\Longrightarrow$ tests the EW Theory

Why at a Hadron Collider?

$$\begin{aligned} \boldsymbol{\Upsilon(4S):}\ & \boldsymbol{\sigma(B\bar{B}) \sim 1\ \mathrm{nb}}\ (\bar{B}^0 \text{ and } B^- \text{ only}) \\ \boldsymbol{Z^0:}\ & \boldsymbol{\sigma(b\bar{b}) \sim 7\ \mathrm{nb}} \\ \boldsymbol{p\bar{p}:}\ & \boldsymbol{\sigma(p\bar{p} \to b\bar{b}X) \sim 100\ \mu\mathrm{b}}\ (\text{at } \sqrt{s} = \mathbf{1.8}\,\mathrm{TeV}) \end{aligned}$$

BUT inelastic cross-section 10^3 larger
$\Longrightarrow$ requires specialized triggers

Run I

- Inclusive lepton ($\ell = e, \mu$) triggers

  $b \to \ell\nu cX$ or $b \to cX, c \to \ell\nu Y$

  $\langle p_T(B)\rangle \approx 20\,\mathrm{GeV}/c$

- Dilepton (μe, $\mu\mu$)triggers

  $b \to J/\psi X, \psi \to \mu^+\mu^-$

  $b \to \mu^- X, \bar{b} \to e^+ Y$

  $\langle p_T(B)\rangle \approx 10\,\mathrm{GeV}/c$

Run II

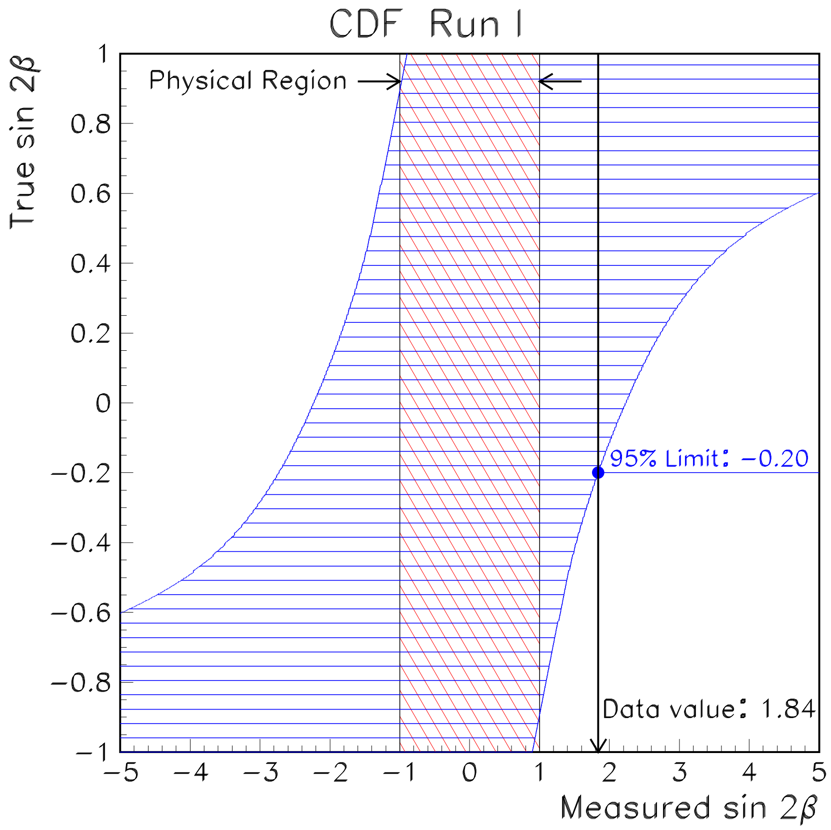
Exploit B lifetime $\Longrightarrow$ trigger on displaced tracks
All hadronic B trigger possible
e.g., $B^0/\bar{B}^0 \to \pi^+\pi^-$, $B_s^0 \to D_s^-\pi^+$

First Measurement of $\sin(2\beta)$ (2)

Using $D = 0.166 \pm 0.018(\mathrm{data}) \pm 0.013(\mathrm{MC})$

Find $\sin(2\beta) = 1.8 \pm 1.1\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst})$
(Systematic error includes uncertainty on dilution)

Nonphysical result $\Longrightarrow$ exclude allowed region:



Limit: $-0.2 < \sin(2\beta)$ at 95% C. L.

(sensitivity: $-0.9 < \sin(2\beta)$ at 95% C. L. if $\sin(2\beta) = 1$)

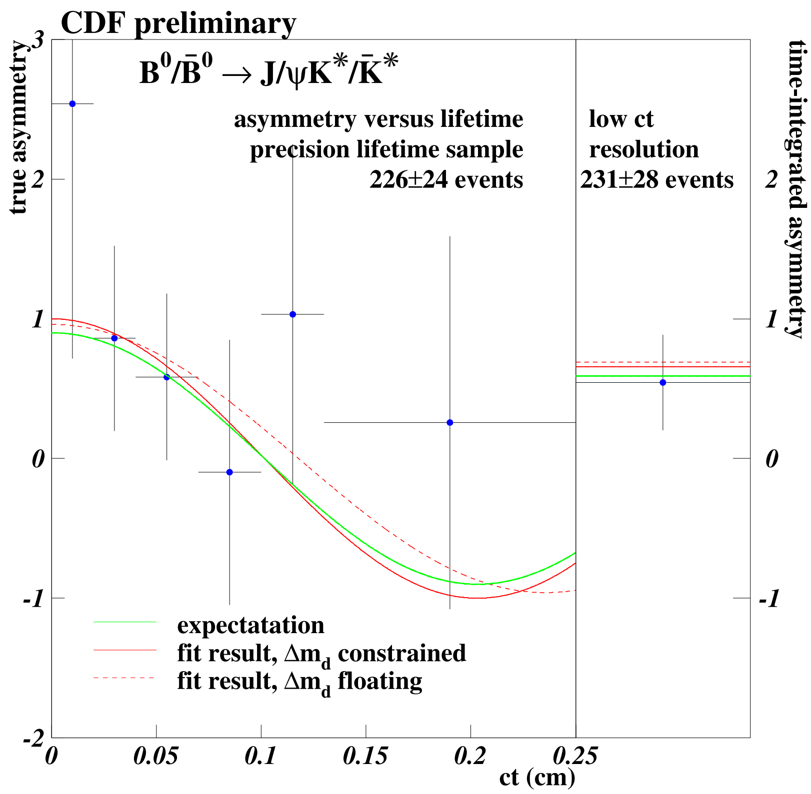
Preliminary Update of sin(2β)

Data Set	Tag	sin(2β)	+ error	- error
All	All	0.79	0.41	0.44
	same-side	2.03	0.84	0.77
	jet-charge	-0.31	0.81	0.85
	lepton	0.52	0.61	0.75
SVX	All	0.54	0.52	0.57
(precise t)	same-side	1.77	1.04	1.01
CTC	All	1.24	0.75	0.70

Check with $B^0 \to J/\psi K^{*0}$

Check procedure by fitting for

- Amplitude $\mathcal{A}$
- mass difference $\cos(\Delta m_d)$



Results:

$$\mathcal{A} = 0.96 \pm 0.38$$

$$\Delta m_d = 0.41 \pm 0.18\,\mathrm{psec}$$

Consistent with expectations

Measuring Oscillation Frequency Δm

Classify decays as:

"Unmixed": same b Flavor at production and decay
"Mixed": opposite b Flavor at production and decay

Examine variation with proper decay time t:

$$\mathcal{A}(t) = \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)} = D \cdot \cos(\Delta m t)$$

Flavor tag Dilution: $D = 2 \cdot \mathcal{P} - 1$
($\mathcal{P}$ = probability flavor tag is correct)

Proper time reconstruction:

$$t = m(B) \cdot \frac{L}{p}$$

Uncertainty δt on t:

$$(\delta t)^2 = \left(\frac{m(B)}{p}\delta L\right)^2 \oplus \left(t \cdot \frac{\delta p}{p}\right)^2$$

B_s^0 Flavor Oscillations in Run II

- **Expected signal:** 20000 $B_s^0 \to D_s^- \pi^+, D_s^- \pi^+ \pi^- \pi^+$; $D_s^- \to \phi\pi^-, K^{*0}(892)K^-$ after trigger and selection
- **Proper time resolution:**

$$\sigma_t = 0.060 \text{ ps} \oplus t \cdot \sigma_{p_T}/p_T \text{ (SVXII only)}$$

$$\sigma_t = 0.045 \text{ ps} \oplus t \cdot \sigma_{p_T}/p_T \text{ (SVXII with L00)}$$

- **Flavor tag effectiveness:**

$$\epsilon D^2 = 5.7\% \text{ (CDF Baseline detector)}$$

$$\epsilon D^2 = 11.3\% \text{ (with addition of TOF)}$$

- **Signal to Noise:** 2:1→1:2 (used Run I data)

$$\mathrm{Sig}(x_s) = \sqrt{\frac{N\epsilon D^2}{2}} e^{-(x_s \sigma_{ct}/\tau)^2/2} \sqrt{\frac{S}{1+S}}$$