B Physics at the Tevatron
Recent Results and Future Prospects

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What This Talk Covers

Selected Results from Tevatron Run I

- **August 1992 to February 1996**
- **CDF and D0 collected 100 pb^{-1} of data**

Expected B Physics in Run II

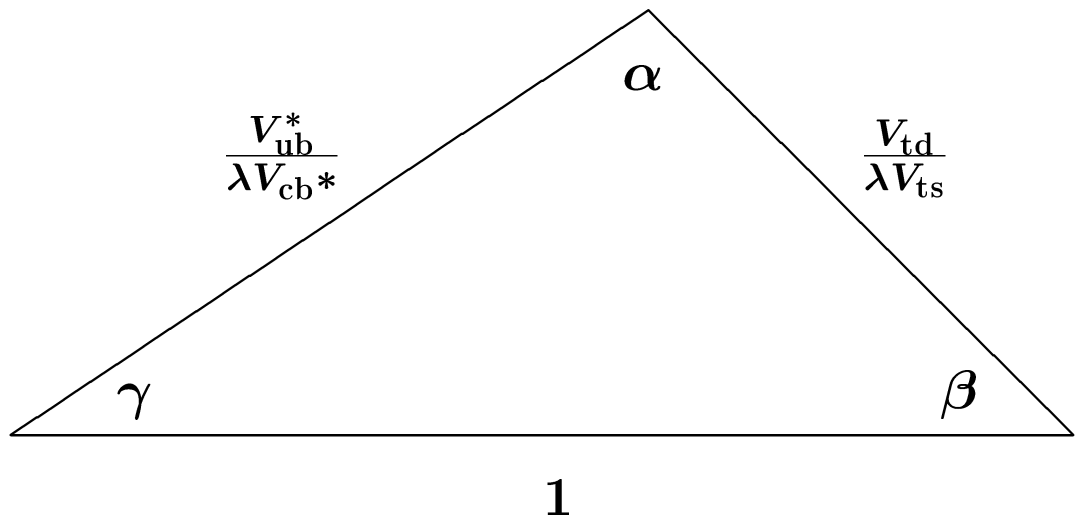
- **Begins in April 2001**
- **Initial Integrated $\mathcal{L} = 2\ \mathrm{fb}^{-1}$**
  Expected in 2 years
- *e.g.*, **10^{11} $b\bar{b}$ per year**

Beyond Run II (if time permits)

- **Possible dedicated B physics exp. (BTeV)**

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 $B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$
2. $|V_{\rm td}/\lambda V_{\rm ts}|$ from $B^0 - \bar{B}^0$ and $B^0_s - \bar{B}^0_s$ flavor oscillations

Unique capability to do both at Had. Coll.

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 $= 1.4$ Tesla; Radius $r = 1.4$ m

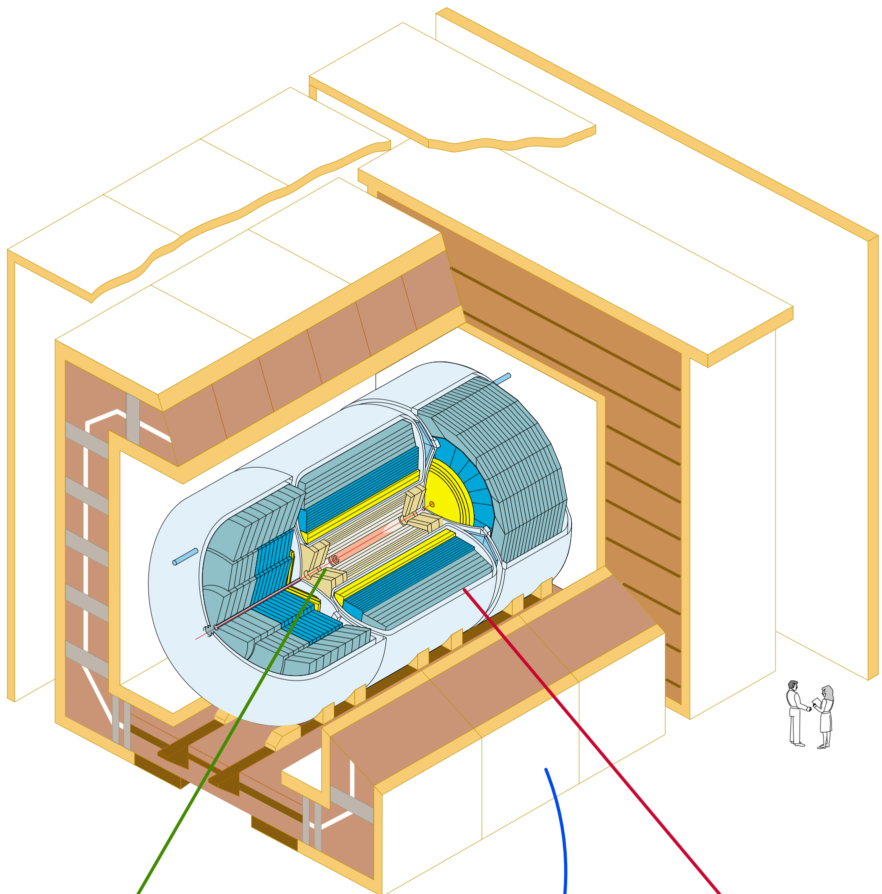
  $(\delta p_T/p_T)^2 = (0.0066)^2 \oplus (0.0009 p_T)^2$

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

  Central e: $|\eta| < 1$

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

The Run I D0 Detector



DØ Detector

TRACKING

σ(vertex)=6 mm
σ(rφ) = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

$|\eta| < 3.3$

$\frac{\delta p}{p} = 0.2 \oplus 0.01p$

CALORIMETRY

$|\eta|<4$

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

$\sigma(EM) = 15\%/\sqrt{E}$

$\sigma(HAD) = 50\%/\sqrt{E}$

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_{cb}, V_{ub}, V_{tb}, V_{ts}, V_{td}

$\Longrightarrow$ tests the EW Theory

Why at a Hadron Collider?

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

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

Run I

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

  $b \to \ell\nu c X$ 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

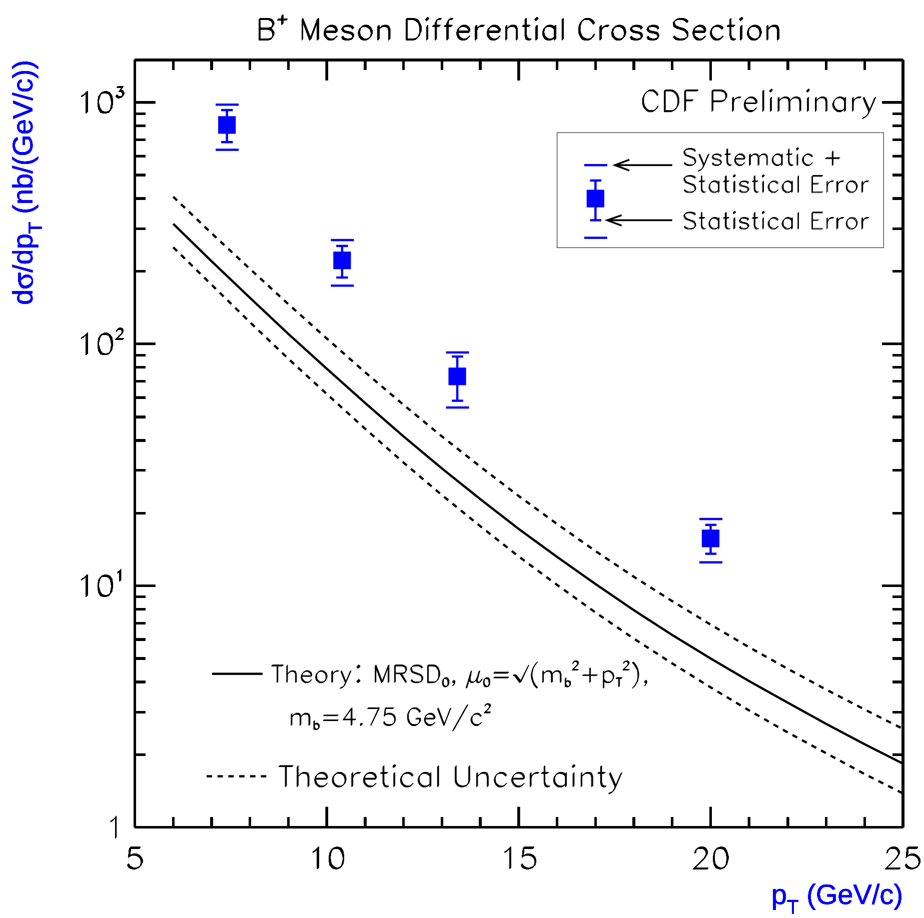
- Trigger on displaced tracks (exploit $\tau(B)$)

  All hadronic B trigger possible

  e.g., $B^0/\bar{B}^0 \to \pi^+\pi^-$, $B_s^0 \to D_s^-\pi^+$

B Meson Cross Section

"Useful" B meson cross section



$$\sigma(\bar{B}^0, p_T(\bar{B}) > 6\,\mathrm{GeV}/c, |y(\bar{B})| < 1)$$
$$= 3.51 \pm 0.42\,(\mathrm{stat}) \pm 0.53\,(\mathrm{syst})\,\mu\mathrm{b}$$

B Physics is Two Subjects

1. The Study of Weak Decays

$\Longrightarrow$ The emphasis of this talk

Run II: $\bar{B}_s^0$ Λ_b B_c^- unique

2. Quantitative Study of QCD

- $m_b \gg \Lambda_{\text{QCD}} \Longrightarrow$ inclusive production calculable with Perturbation Theory.
- Probe gluon structure func: $gg \rightarrow b\bar{b}$.
- At Tevatron NLO (α_s^3) corrections as large as L0 (α_s^2)
- unique to hadron colliders (like $\Gamma_{b\bar{b}}$ on Z^0)

Not covered in this talk

Run I B Physics Results: Highlights

- Precise mass measurements of $\bar{B}_s^0$ and Λ_b
- Precise inclusive and species specific B lifetime measurements
- Neutral B meson flavor oscillations
  - Precise measurement of Δm_d
  - lower limit on Δm_s
  - developed b flavor tags
- Search for rare/forbidden B decays
  - FCNC: *e.g.*,$\bar{B}^0, \bar{B}_s^0 \to \mu^+\mu^-, B^- \to \mu^+\mu^- K^-$
  - Lepton number violation: $\bar{B}^0, \bar{B}_s^0 \to \mu^\pm e^\mp$
- Polarization in $\bar{B}^0 \to J/\psi \bar{K}^{*0}$ $B_s^0/\bar{B}_s^0 \to J/\psi\, \phi$
- Discovery of B_c^- from $B_c^- \to J/\psi \ell X, \ell = e, \mu$
- First measurement of $\sin(2\beta)$ from $B^0/\bar{B}^0 \to J/\psi K_S^0$

Run I B Physics Results (cont.)

- incl. diff. cross sections (b and B) at $\sqrt{s} = 630$ & $1800\,\mathrm{GeV}$
- correlated $b\bar{b}$ production (φ and y)
- Relative production rates (f_u, f_d, f_s, f_{baryon})
- Precise relative branching fractions
- Studies of prompt and non-prompt $J/\psi, \psi(2S)$ production including polarization
- $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ production
- $\chi_c(1P), \chi_c(2P), \chi_b$ production

In total: over 40 publications submitted or published

B Hadron Lifetimes

Three types of measurements

1. Inclusive: $b \to J/\psi X$

largest statistics: $\sim 11\,000$ $b \to J/\psi X$

not species specific $\Longrightarrow$ does not test models

2. Species specific: partially reconstructed

$\bar{B}^0$ B^- $\bar{B}^0_s$ Λ_b B^-_c

Examples: $\bar{B}^0 \to \ell^- \bar{\nu}_\ell D^{(*)+}, B^- \to \ell^- \bar{\nu}_\ell D^0$

good statistics: 200 to 6 000 depending on channel

cross contamination (signature ambiguities)

3. Species specific: fully reconstructed

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

Examples: $B^- \to J/\psi K^-, \bar{B}^0_s \to J/\psi\,\phi$

lowest statistics: 60 to 500 depending on channel

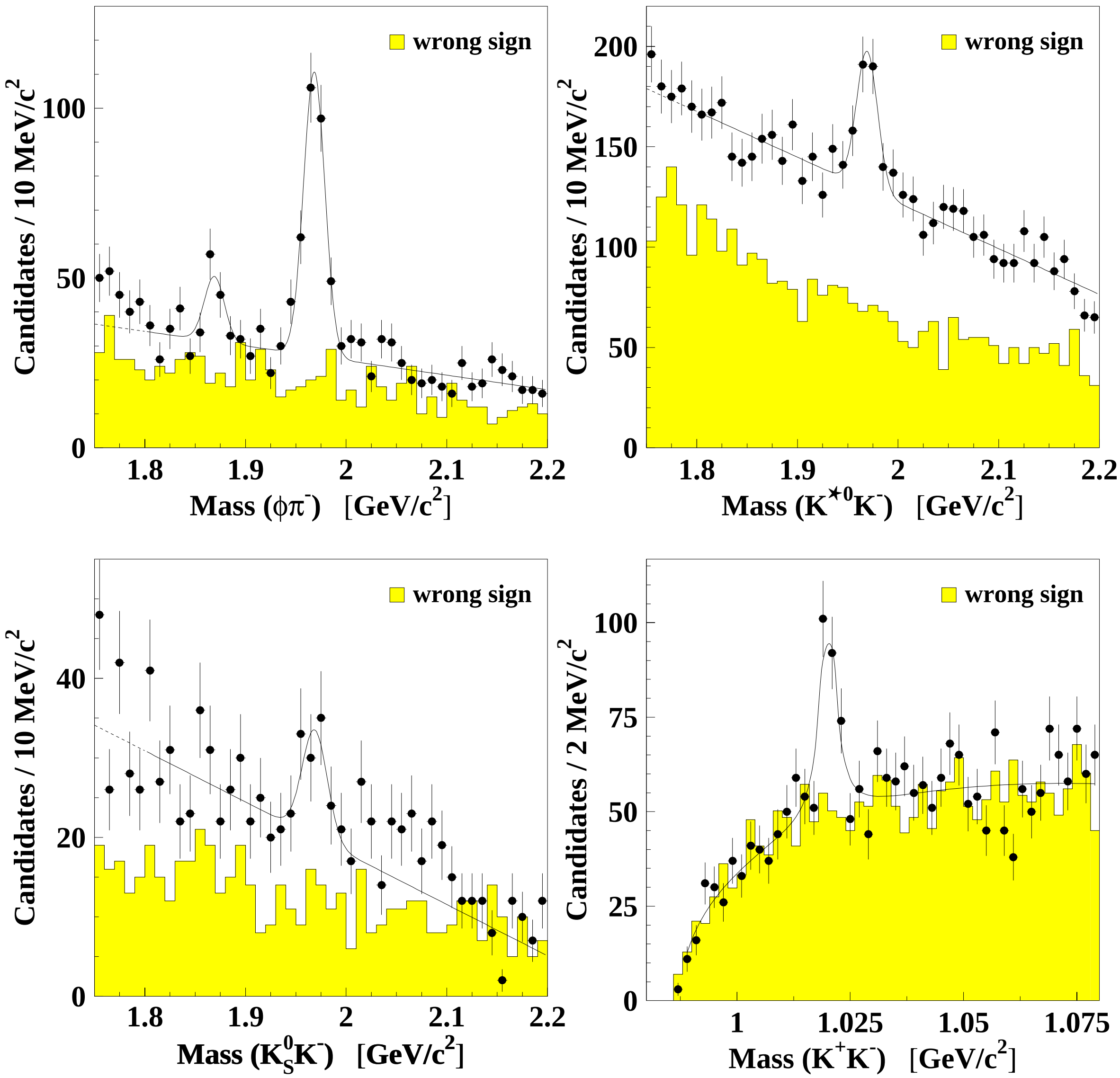
BUT cleanest recontruction and signal

Run II: Test Models to 1%

$B_s^0 \to D_s^- \ell^+ \nu_\ell X$: $\tau(B_s^0)$ and $\Delta\Gamma_s/\Gamma_s$

F. Abe *et al.*, Phys. Rev. D **59**, 032004 (1999)

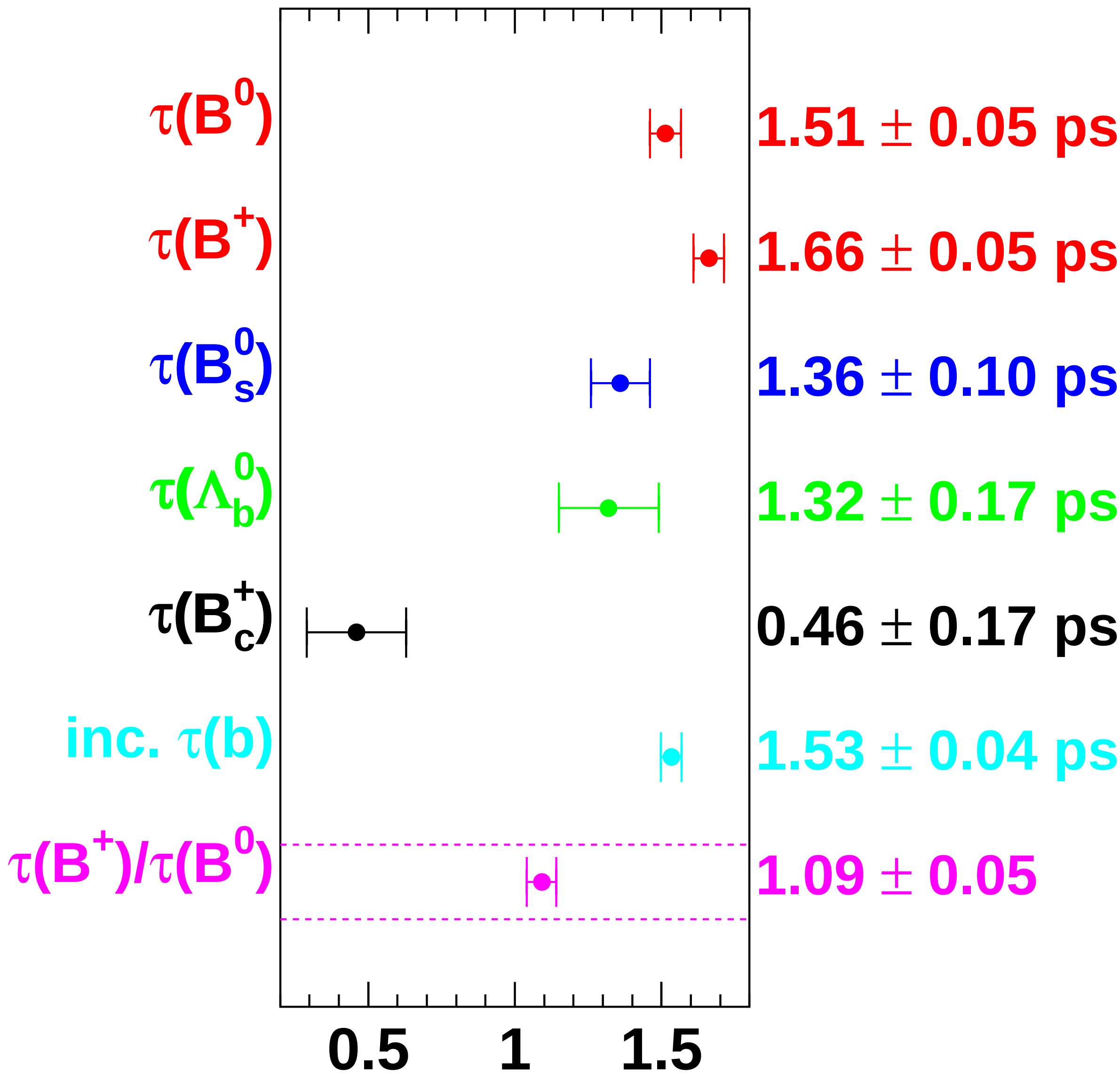
Signal ≈ 600



$$\tau(B_s^0) = 1.36 \pm 0.09^{+0.06}_{-0.05}\ \text{ps}$$

$$\Delta\Gamma_s/\Gamma_s < 0.83 \text{ at } 95\% \text{ C.L.}$$

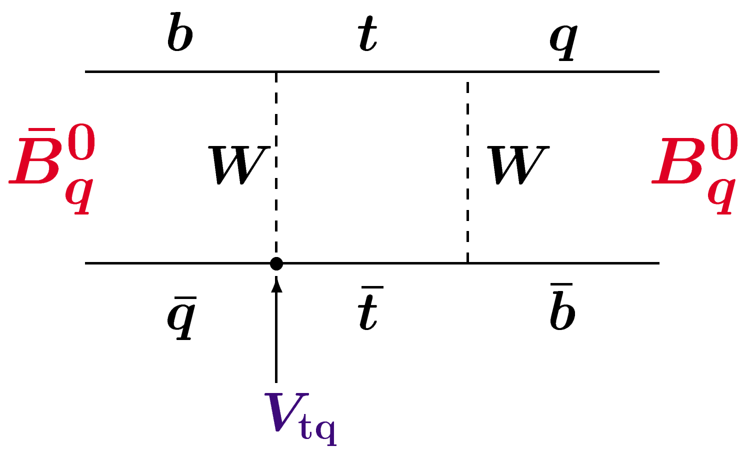
CDF B Lifetimes



All Published

Neutral B Meson Flavor Oscillations

Due to 2nd Order Weak Int. *e. g.* $(q = d, s)$



If initial state is B^0_q

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

$$\mathcal{P}(\bar{B}^0_q(t)) = \frac{1}{2}\Gamma e^{-\Gamma t}(1 - \cos\Delta m_q t)$$

The oscillation frequency Δm_q is given by

$$\Delta m_q = \frac{G_{\rm F}^2}{6\pi} m_B m_t^2 F\left(\frac{m_t^2}{m_W^2}\right)\eta_{\rm QCD} B f_B^2 |V_{\rm tb}^* V_{\rm tq}|^2$$

Since $V_{\rm ts} \gg V_{\rm td}$, B^0_s oscillates faster than B^0_d

$$\frac{|V_{\rm td}|}{|V_{\rm ts}|} = (1.16 \pm 0.06) \cdot \sqrt{\frac{\Delta m_d \cdot m(B^0_s)}{\Delta m_s \cdot m(B^0)}}$$

Measuring B Flavor Oscillations

To measure Δm

I. Time integrated measurement

$$\chi = \frac{x^2}{2(1+x^2)}, x = \frac{\Delta m}{\Gamma} = \Delta m \cdot \tau$$

measure χ, determine Δm
as $\Delta m \to \infty, \chi \to \frac{1}{2}$

II. Measure proper time dependence

Produce B^0, measure probability $\mathcal{P}(B^0 \to \bar{B}^0)$ as a function of proper decay time t

Requires

1. Flavor of B at production
   often use other $\bar{B}$ for this
   Crucial for CP Asymmetries
2. Flavor of B at decay
   ($e.g.$, Lepton charge in $B \to \ell X$)
3. Proper decay time t of B

Methods of b Flavor Tagging

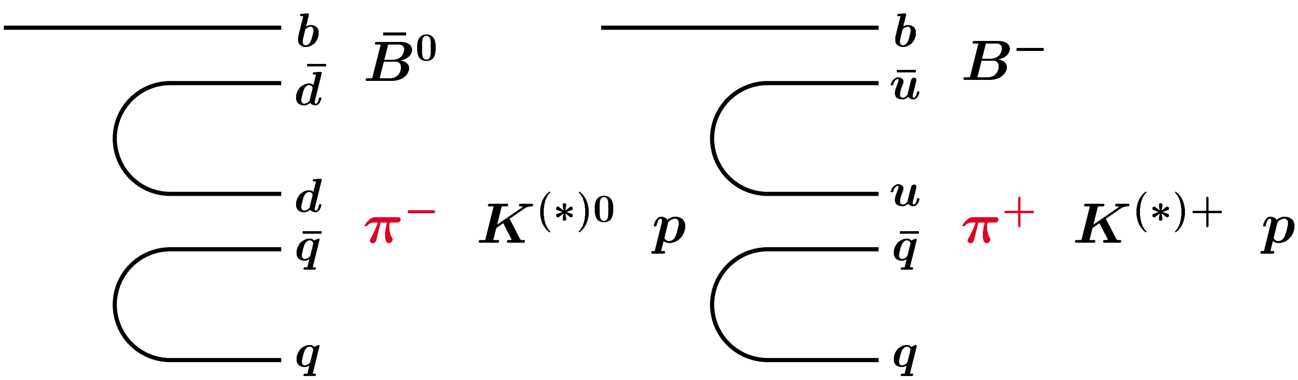
1. Opposite-side flavor tags (OST)

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: $Q^b_{\mathrm{jet}} < 0$, but $Q^{\bar{b}}_{\mathrm{jet}} > 0$**
- **$\sim 40\%$ 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

Measuring Oscillation Frequency Δm

Classify decays as:

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

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

Data Samples for Δm_d at CDF

Triggers (incl. ℓ, dilepton) dictate approaches

In some cases (†) trigger on flavor tag (lepton)

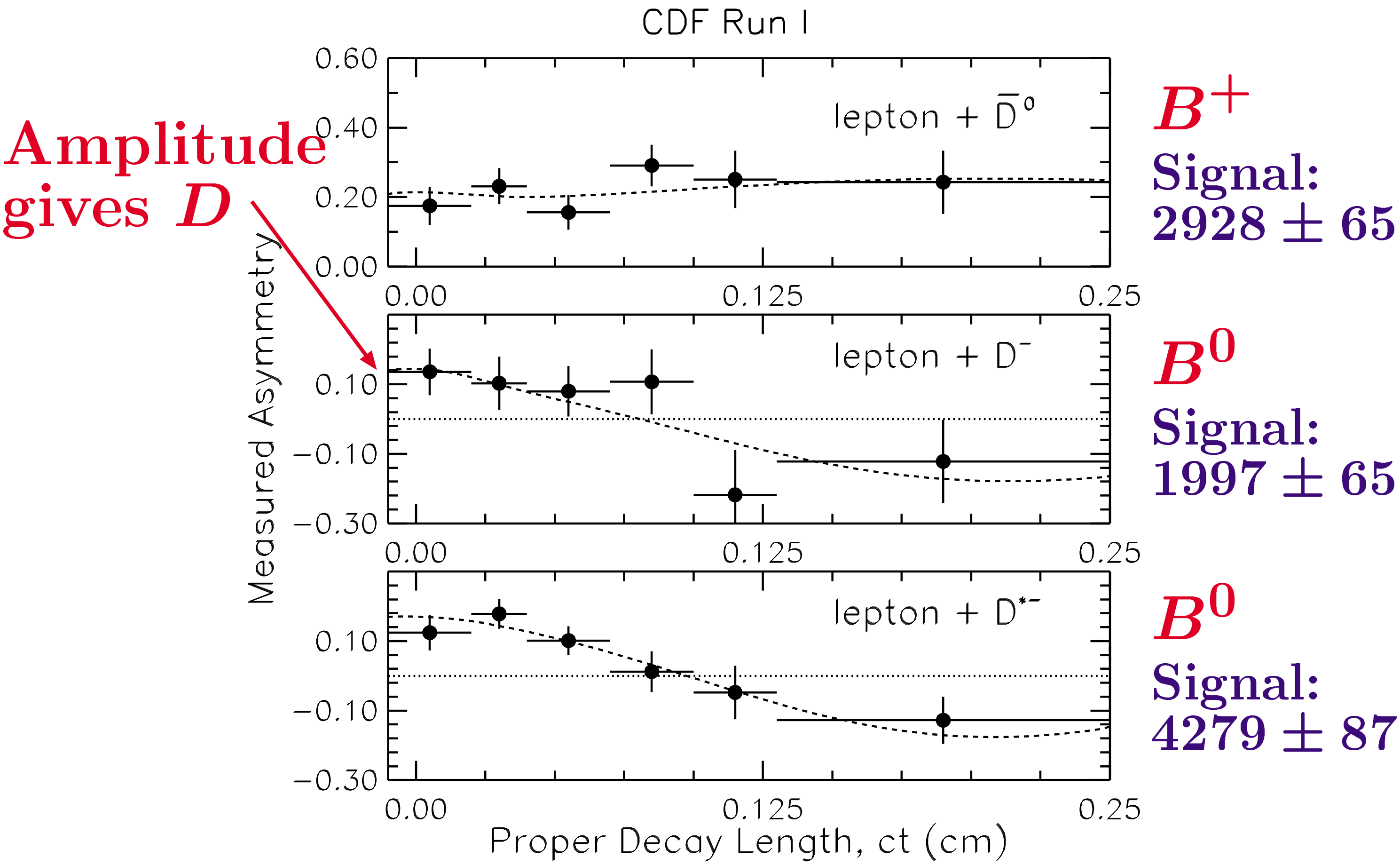
Other cases tag unbiased by trigger $\Longrightarrow$
most useful for studying tags for CP violation

However, Run II trigger strategy for CP
may include triggering on lepton tags

Channel	B Decay Point	Flavor Tag
Inclusive lepton $\ell = e$ or μ	Associate ℓ to secondary vertex	Jet-Charge soft-lepton
Dilepton $e\mu$, $\mu\mu$	Associate ℓ to secondary vertex	other lepton (†)
lepton vs. fully Recons. D	D^* or D^- decay point	trigger lepton (†)
Partially recons. $B \rightarrow \ell D X$	lepton + D decay point	same-side pion tag
lepton versus $\ell + D$	lepton + D decay point	other lepton (†)
Fully recons. $B \rightarrow J/\psi K$	B decay point	any of above

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).

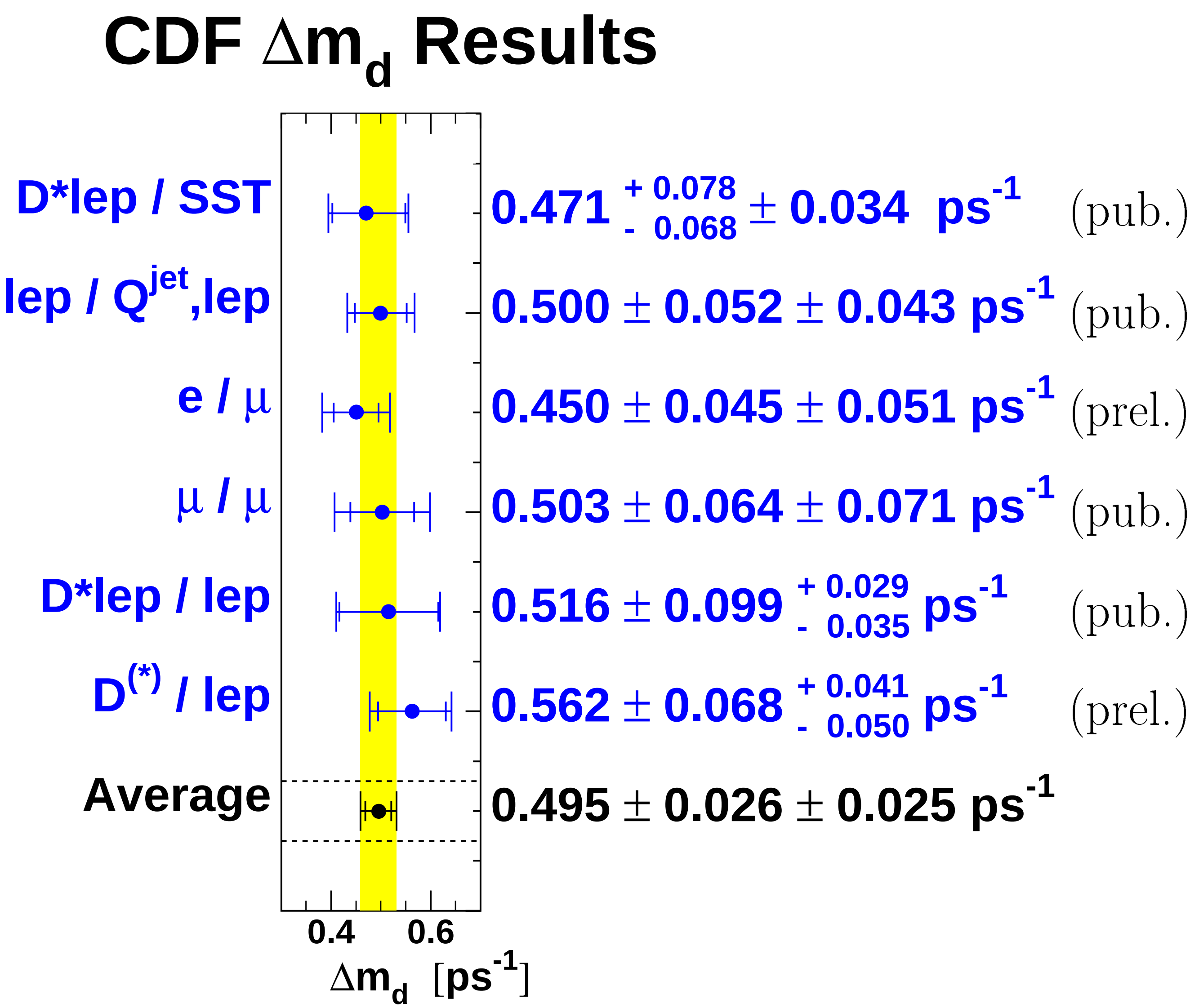


Measure efficiency ϵ and dilution D of tag:

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

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

CDF B Mixing Results



pub. = published; sub. = submitted; prel. = preliminary

Limit: $\Delta m_s > 5.8$ **ps**$^{-1}$ **at 95% C. L.**$(\ell$ **vs.** $\ell\phi)$

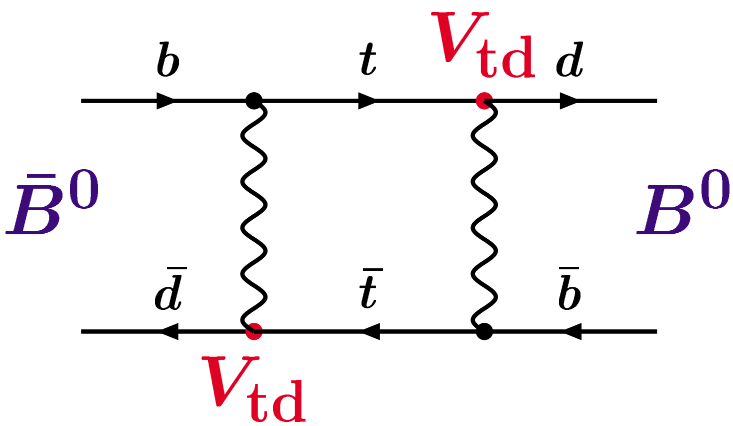
(F. Abe *et al.*, Phys. Rev. Lett. **82** (1999) 3576.)

CP Violation in B Decays

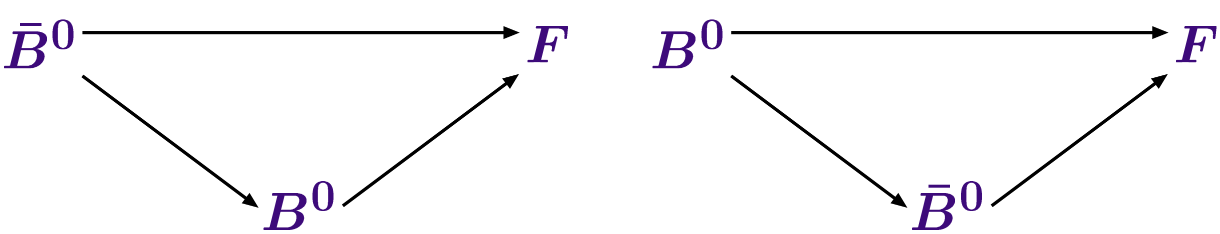
Cleanest measurements use

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

CP Violation induced by mixing



V_{td} puts complex phase in Weak Amplitude



Two paths (amplitudes) to F interfere

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

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

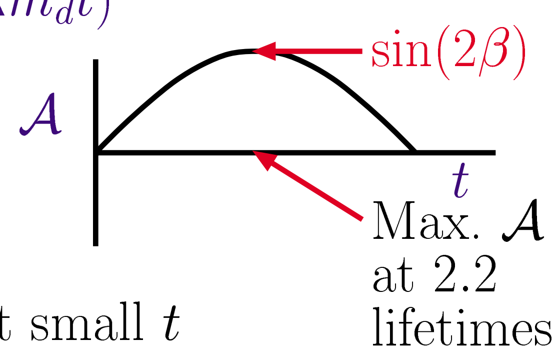
$$\mathcal{A}_{CP} = \frac{x_d}{1+x_d^2}\sin 2\beta \approx 0.5 \sin 2\beta$$

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



Overview of Analysis (1)

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

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

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

To accomplish this we must:

1. Reconstruct signal $B^0/\bar{B}^0 \to J/\psi\, K^0_{\rm S}$
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

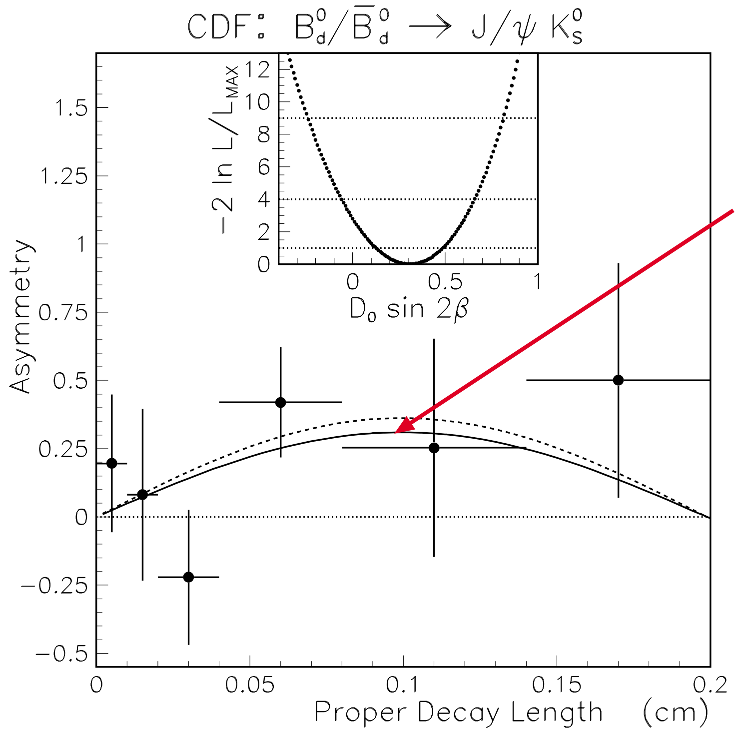
Note: $\epsilon D^2 \sim 1\%$ or larger is respectable

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)

Improved Measurement of sin(2β)

Accepted for publication in PRD
T. Affolder *et al.*, FERMILAB-Pub-99/225-E, hep-ex/9909003

Improve statistical power of first result

1. **Add candidates not fully reconstructed in silicon vertex detector (SVX)**

   doubles signal to $\approx$ 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 $\mathcal{L}$

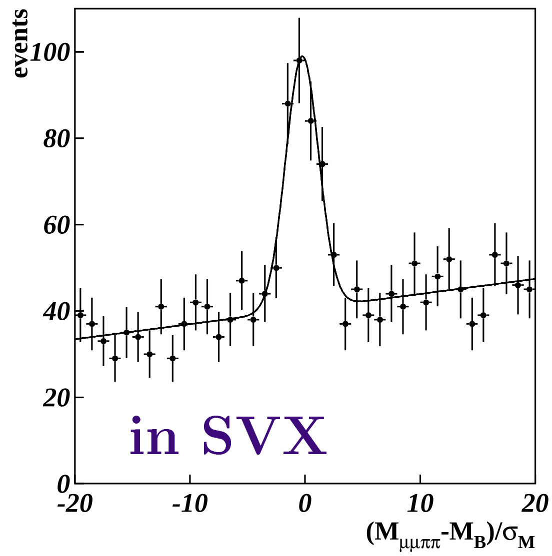
Include terms in likelihood for

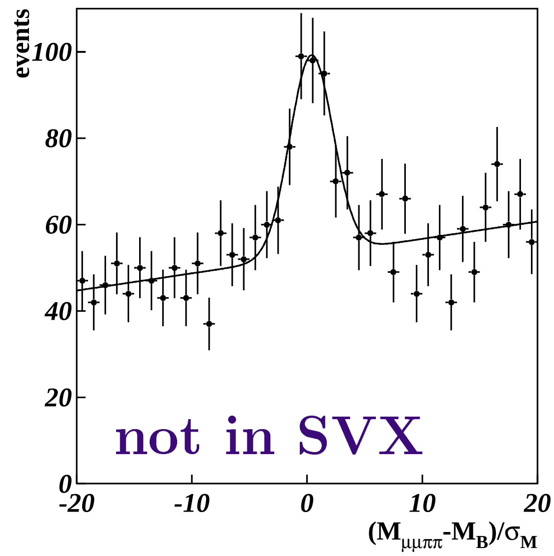
- **Possible detector biases**
- **prompt background:**
  $p\bar{p} \to J/\psi X$ + random K^0_S
- **long-lived background:**
  $B \to J/\psi X$ + random K^0_S

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

Add candidates not fully contained in SVX

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

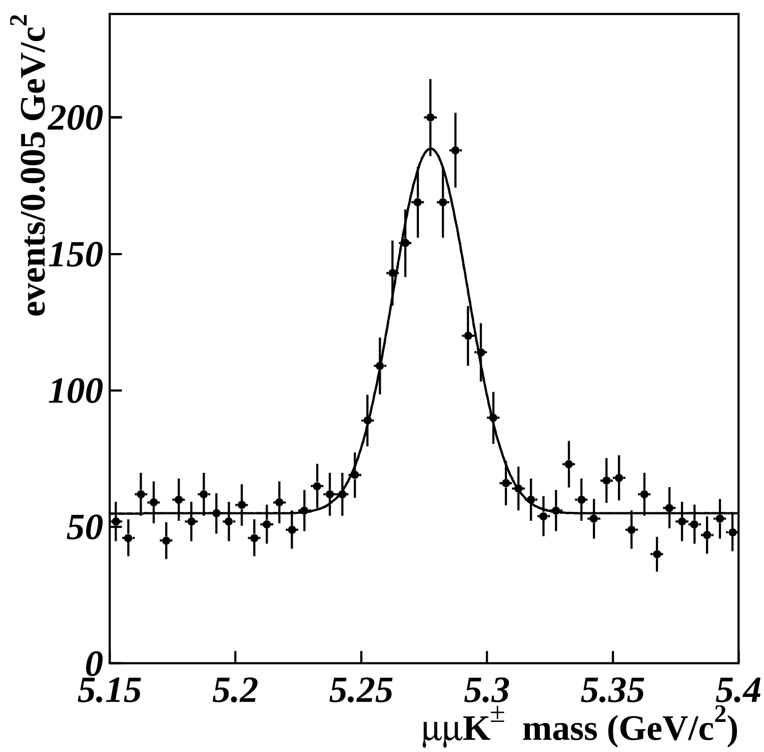
(F. Abe *et al.*, Phys. Rev. **D60** (1999) 072003, hep-ex/9903011)

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:**

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

   $\epsilon = (5.6 \pm 1.8)\%$

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

   $\epsilon D^2 = (2.2 \pm 1.2)\%$

2. **Jet Charge:**

   IF soft lepton, do not use Jet Charge

   $\epsilon = (40.2 \pm 3.9)\%$

   $D = (23.5 \pm 6.9)\%$

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

3. **Same side pion:**

   $\epsilon \approx 70\%$

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

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

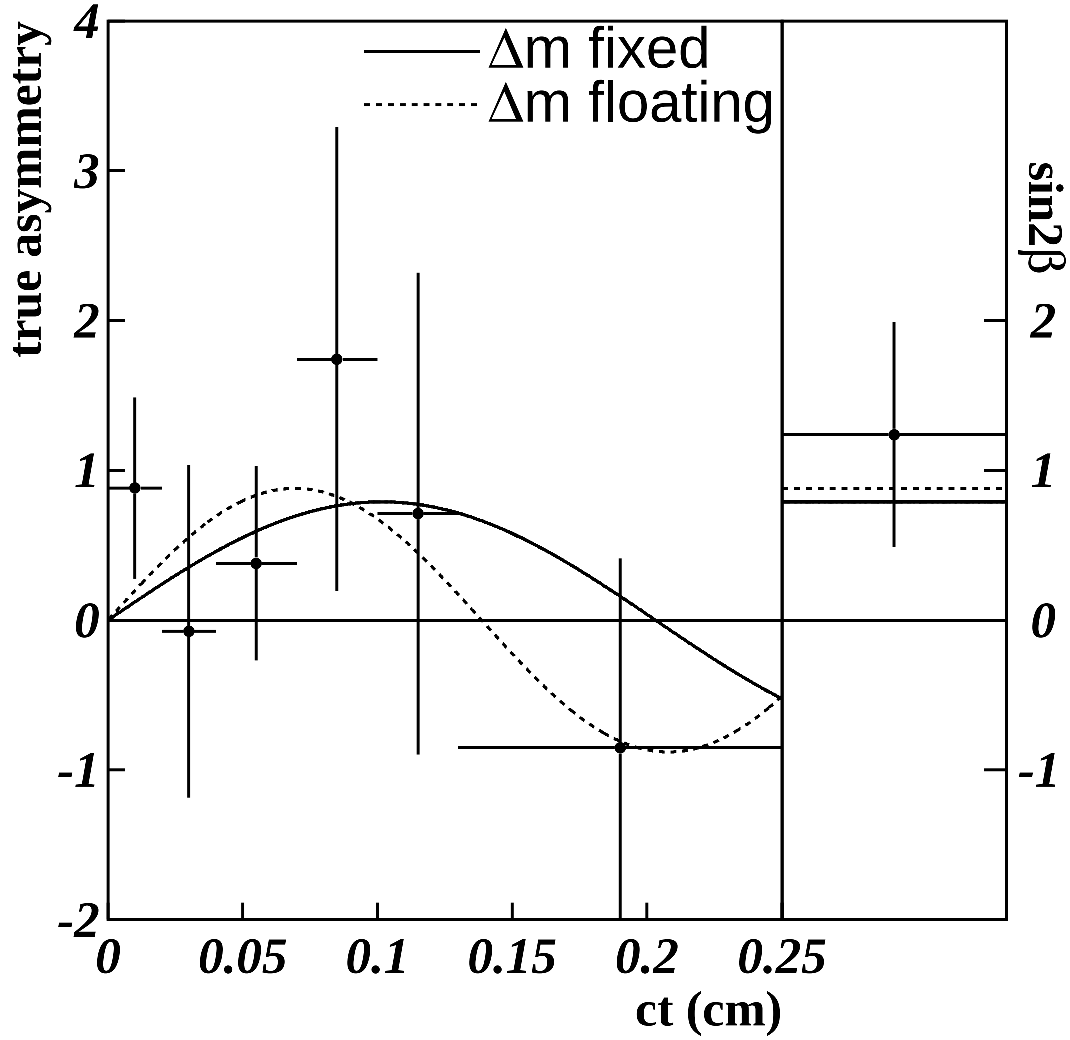
   $\epsilon D^2 = (2.1 \pm 0.5)\%$

Combined Tagging efficiency

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

80% of the candidates have a tag

Measurement of sin(2β)



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

(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	negligible
τ_{B^0}	in fit	negligible
m_B	refit	negligible
trigger bias	external	negligible
K_L^0 regeneration	external	negligible

Let Δm_d float in fit

$$\sin 2\beta = 0.88^{+0.44}_{-0.41}$$

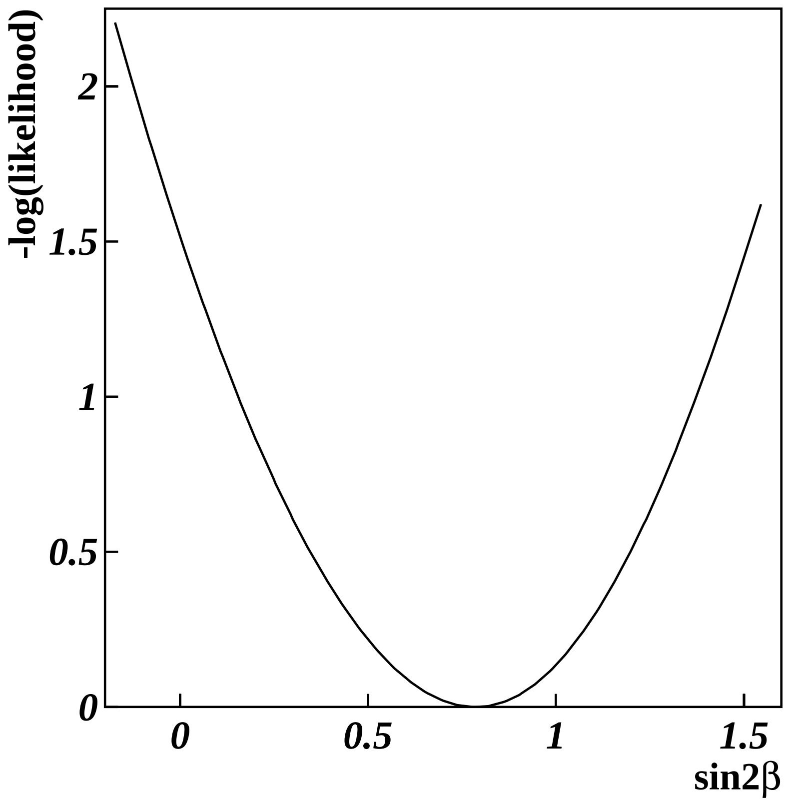
$$\Delta m_d = 0.68 \pm 0.17\,\mathrm{ps}^{-1}$$

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

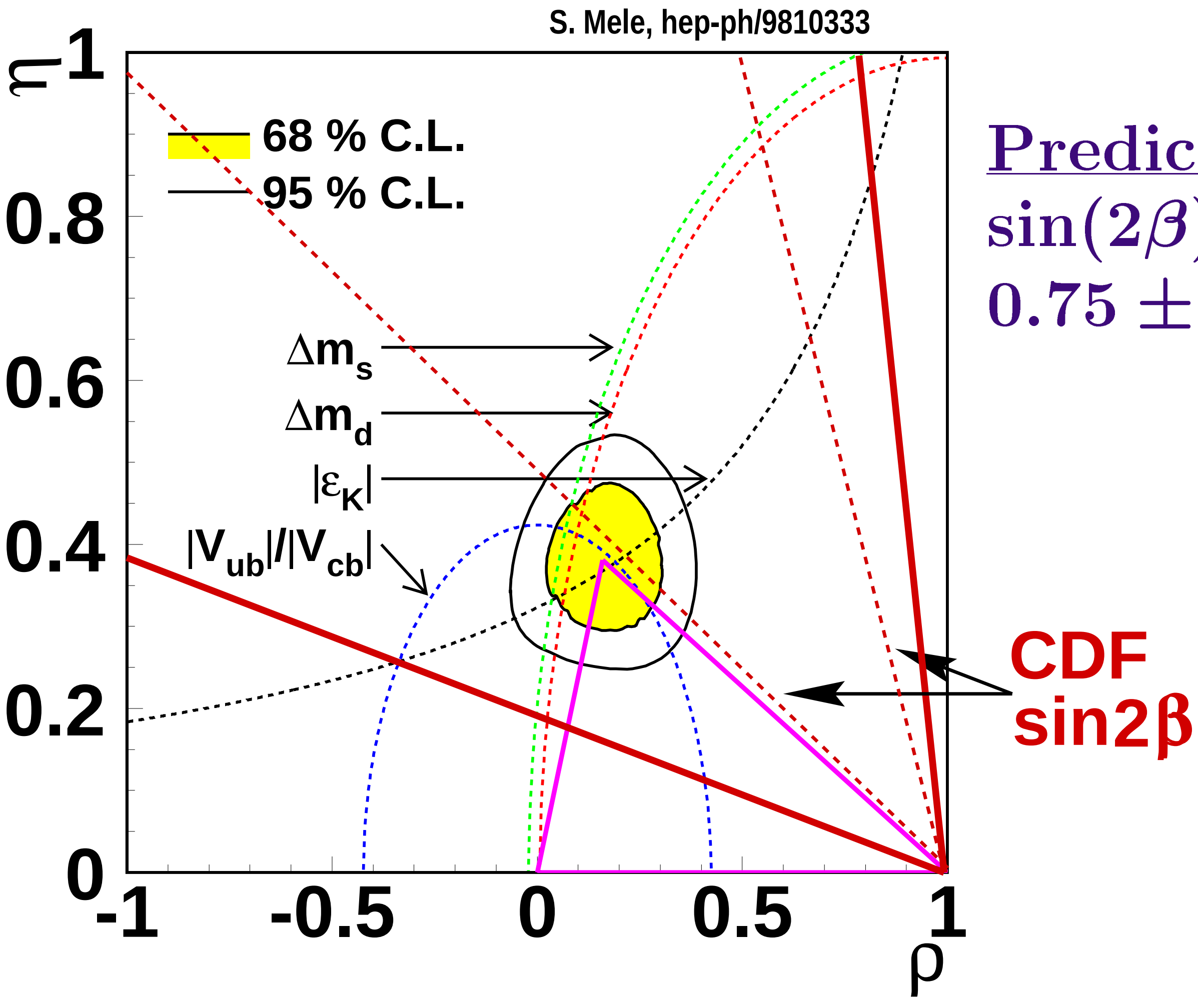
Confidence Limits on $\sin(2\beta)$

Uncertainties ~ 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% C.L.**
- **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

Measurement of $\sin(2\beta)$

Data Subsets

Data Set	Tag	$\sin(2\beta)$	+ 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

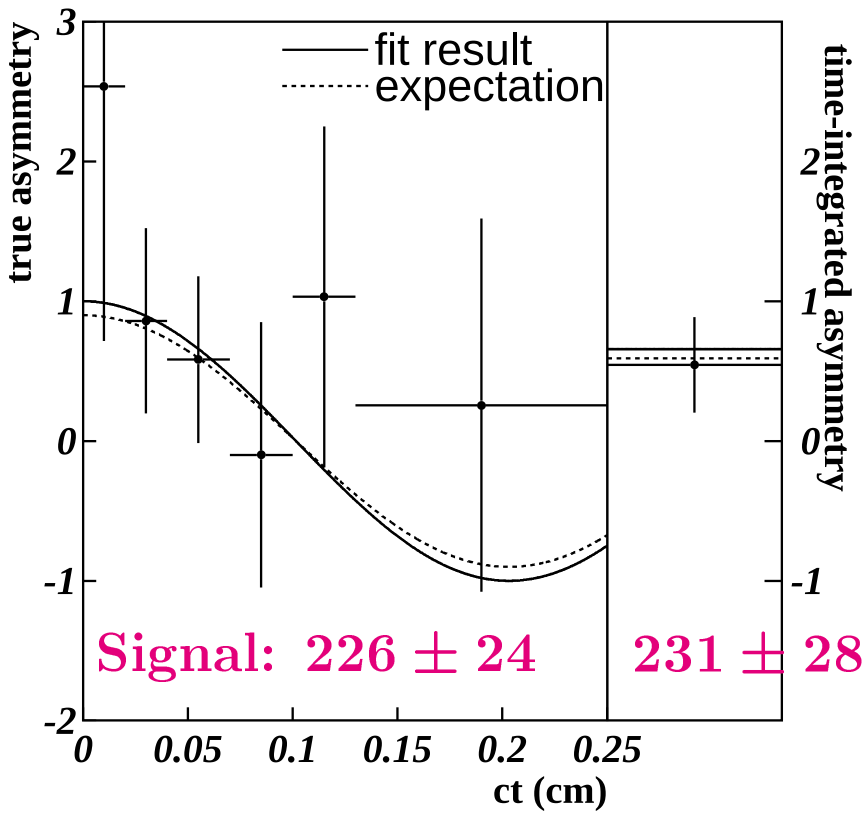
Combined χ^2 of 3 tags:

$\chi^2 = 4.63$ for 2 d.o.f. (Probability=10%)

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

Check procedure by fitting for

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



Results:

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

$$\Delta m_d = 0.40 \pm 0.18\,\text{ps}^{-1}$$

Consistent with expectations

$B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$

Transversity analysis

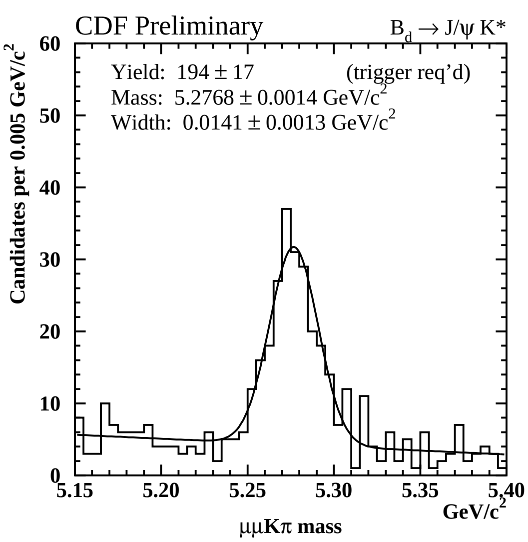
Fit angular distribution for
3 complex amplitudes: A_0, $A_\parallel$, $A_\perp$

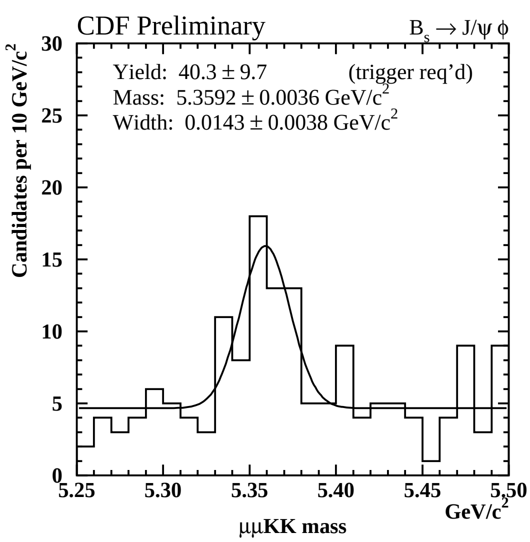
Yields CP composition
$A_\perp$ is parity-odd ($L = 1$) contribution

Is $B_s^0 \to J/\psi\phi$ a pure CP state?

Tests factorization hypothesis

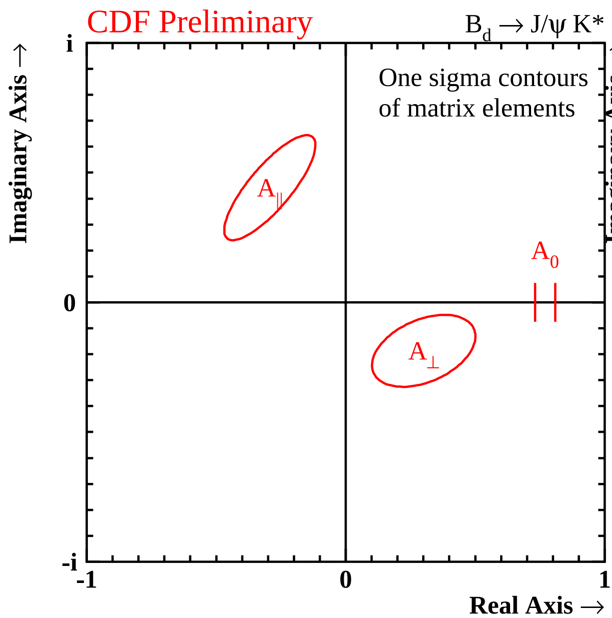
Signals:





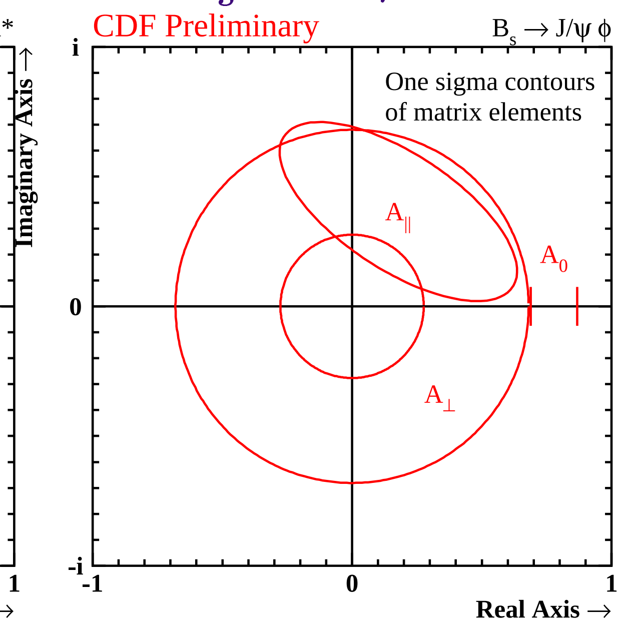
Results on $B \to VV$

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



Fit result: Matrix Elements

$B_s^0 \to J/\psi\phi$



Fit result: Matrix Elements

Observations:

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

non-zero phases imply factorization in question

$B_s^0 \to J/\psi\phi$:

$$|A_\perp|^2 = 0.229 \pm 0.188\,(\text{stat}) \pm 0.038\,(\text{syst})$$

$$|A_\perp|^2 = 0 \Longrightarrow \text{pure } CP \text{ even -- Run II}$$

Rare B Decays

Limits on $B^0/B_s^0 \to \mu^+\mu^-$ (F. Abe et al., PRD **57**, R3811 (1998))

- Allowed in SM, but 3 orders of magnitude below our current sensitivity
- Some SUSY models predict substantial enhancement

$$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 8.6 \times 10^{-7} \text{ (95\%CL)}$$
$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) < 2.6 \times 10^{-6} \text{ (95\%CL)}$$

Limits on $B^0/B_s^0 \to e^\pm\mu^\mp$ (F. Abe et al., PRL **81**, 5742 (1998))

- Forbidden in SM
- Sensitive to new particles: Pati-Salam Leptoquarks

$$\mathrm{BR}(B^0 \to e^\pm\mu^\mp) < 4.5 \times 10^{-6} \text{ (95\%CL)}$$
$$\mathrm{BR}(B_s^0 \to e^\pm\mu^\mp) < 8.2 \times 10^{-6} \text{ (95\%CL)}$$

Corresponding to

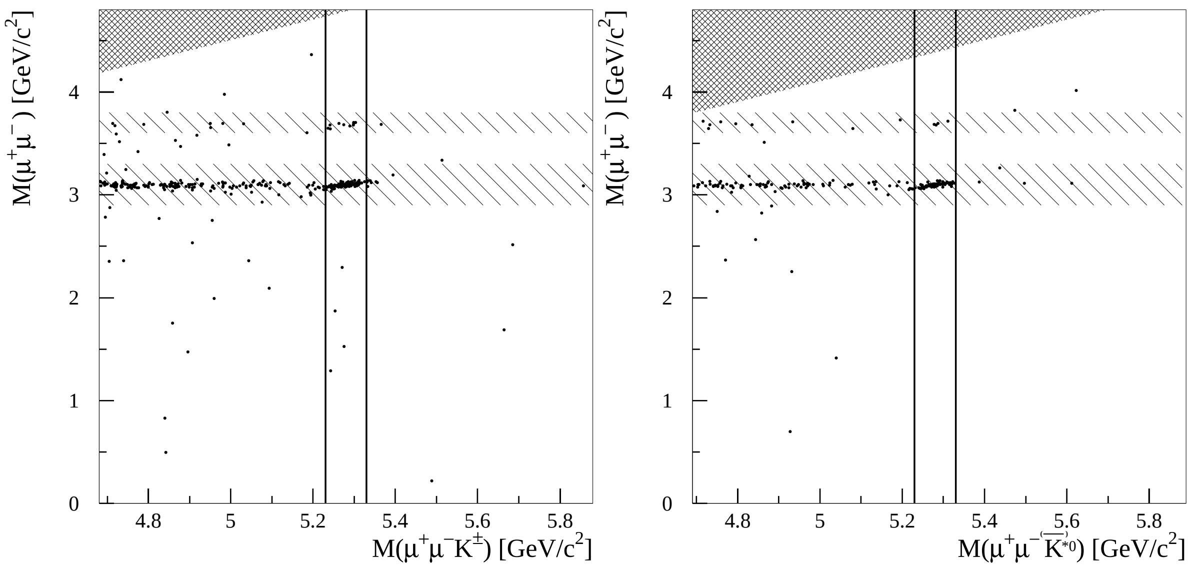
$$M_{\mathrm{LQ}}(B^0) > 20.4\,\mathrm{TeV}/c^2 \text{ (95\%CL)}$$
$$M_{\mathrm{LQ}}(B_s^0) > 19.3\,\mathrm{TeV}/c^2 \text{ (95\%CL)}$$

Run II:

- **Current limits not limited by background**
  Limits should scale with luminosity
- **Sensitive to $M_{\mathrm{LQ}} > 30\,\mathrm{TeV}/c^2$**

Nonresonant $B \to \mu\mu K$

Run I:



- Expect 0.5 Events in each channel from SM
- Comparable level of background

$$\mathbf{BR}(B^+ \to \mu^+\mu^- K^+) < 5.2 \times 10^{-6} \ (90\%\mathrm{CL})$$
$$\mathbf{BR}(B^0 \to \mu^+\mu^- K^{*0}) < 4.0 \times 10^{-6} \ (90\%\mathrm{CL})$$

Run II:

- Should see signal in Run II
- But statistics too low for new physics studies

Tevatron Run I B Physics Summary

Many Interesting and Important Results

- Measurement of Weak Decays
  - Precise species specific lifetimes
  - B flavor oscillations and flavor tagging
  - CP asymmetry and $\sin 2\beta$
  - Discovery of B_c^-
  - Precise mass measurements
  - Rare decays
  - BFs and polarization studies
- Quantitative Test of Perturbative QCD

  Many important results

  Not covered in this talk

Preparation for the real thing: Run II

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 Viol. in $B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$**
  Precise measurement of $\sin(2\beta)$
- **Observe CP Viol. in $B^0/\bar{B}^0 \to \pi^+\pi^-$**
  Precise measurement of asymmetry ($\sin(2\alpha)$)
- (†) **Measure CP asym. in $B_s^0/\bar{B}_s^0 \to J/\psi\,\phi$**
  Large asymmetry is physics beyond SM
- **Observe decay modes related to angle γ**
  $B_s^0 \to D_s^\pm K^\mp$(†) and $B^+ \to \bar{D}^0 K^+$
- **Rare Decays**
  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 Hadron Machines

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:

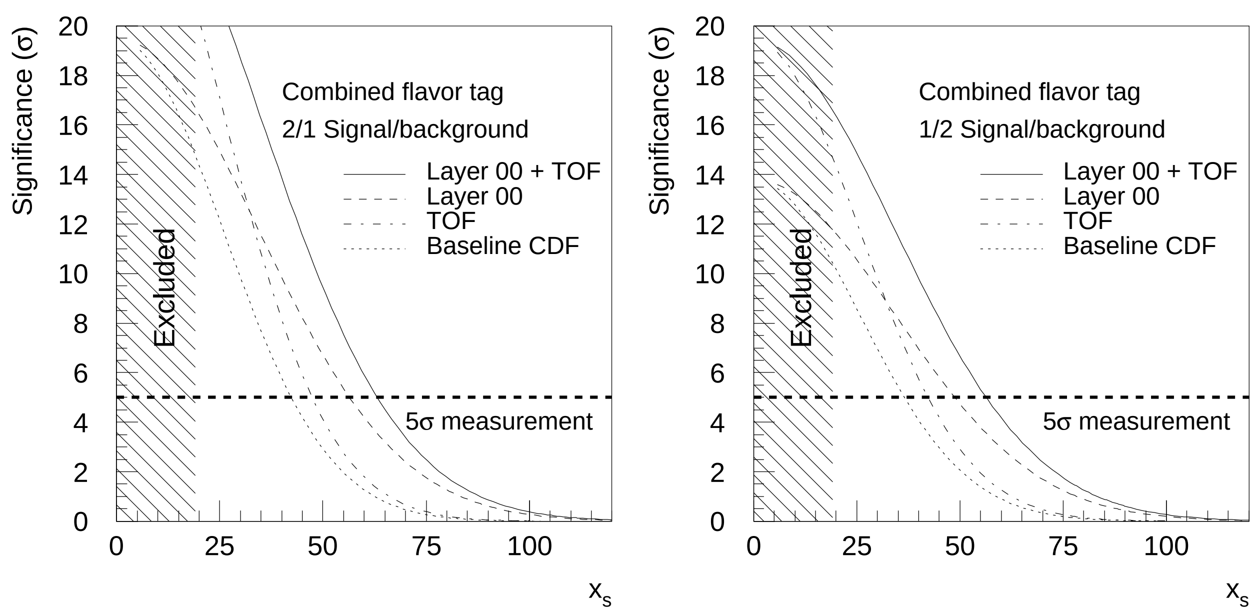
  $\sigma_t = 0.060$ ps $\oplus\, t \cdot \sigma_{p_T}/p_T$ (SVXII only)

  $\sigma_t = 0.045$ ps $\oplus\, t \cdot \sigma_{p_T}/p_T$ (SVXII with L00)
- Flavor tag effectiveness:

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

  $\epsilon D^2 = 11.3\%$ (with addition of TOF)
- Signal to Noise: 2:1→1:2 (used Run I data)

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



Sensitive to $x_s < 63$

Expectations for CP Modes

$\sin 2\beta$ from $B^0/\bar{B}^0 \to J/\psi K^0_S$

- 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)

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

Asymmetry in $B^0/\bar{B}^0 \to \pi^+\pi^-$ ($\sin(2\alpha)$)

- Signal: 8 400 to 15 200 (if BR$= 1.0 \times 10^{-5}$)
- If signal of 10K and $\epsilon D^2 = 9.1\%$

$$\delta\mathcal{A}(\pi^+\pi^-) \sim 0.09$$

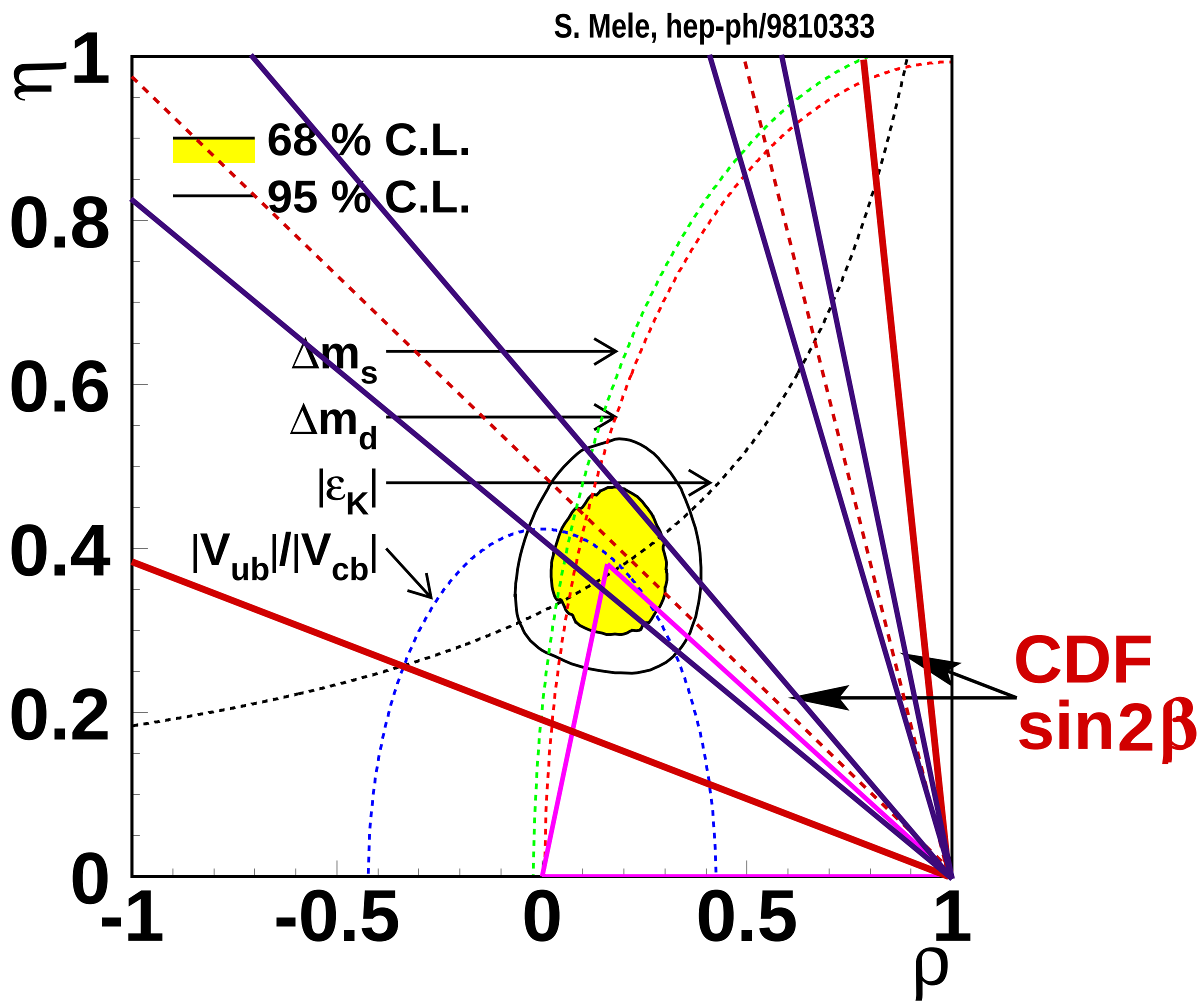
Modes related to $\sin(\gamma)$

- $B^0_s/\bar{B}^0_s \to D^\pm_s K^\mp$ Signal: ~ 700
- $B^\pm \to K^\pm D^0_{CP}$ (direct CP)
- $B^- \to K^- D^0, D^0 \to K^+\pi^-$ and $B^- \to K^- \bar{D}^0, \bar{D}^0 \to K^+\pi^-$

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

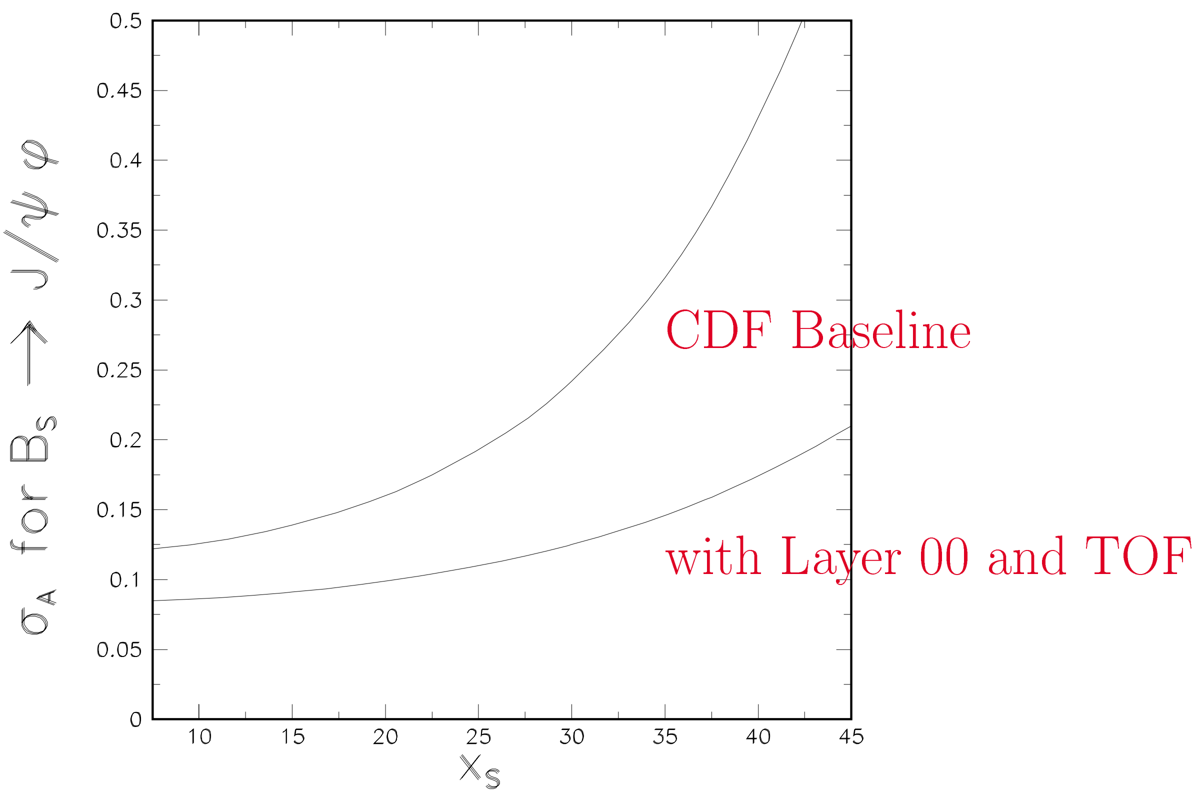
Run I value with proj. Run II error:

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



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

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



Summary

Run I:

Important measurements of B hadron decay properties despite trigger restrictions.

Competitive with e^+e^- colliders.

Gained experience ($\sin 2\beta$, B^0 Flavor oscillations, rare decays) and developed tools (*e.g.*, flavor tags and trigger strategies) for Run II.

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 asym. in B_s^0 decays and Δm_s unique to Hadron machines.

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

Other B Exp. at Hadron Coll.

Near Term

Hera-b (DESY)

- Wire targets in p halo
- $\sigma(b\bar{b})/\sigma(\text{inel}) \sim 10^{-6}$
- lepton and high-p_T hadron trigger
- data taking beginning 2000 (now)

About 5 years from now

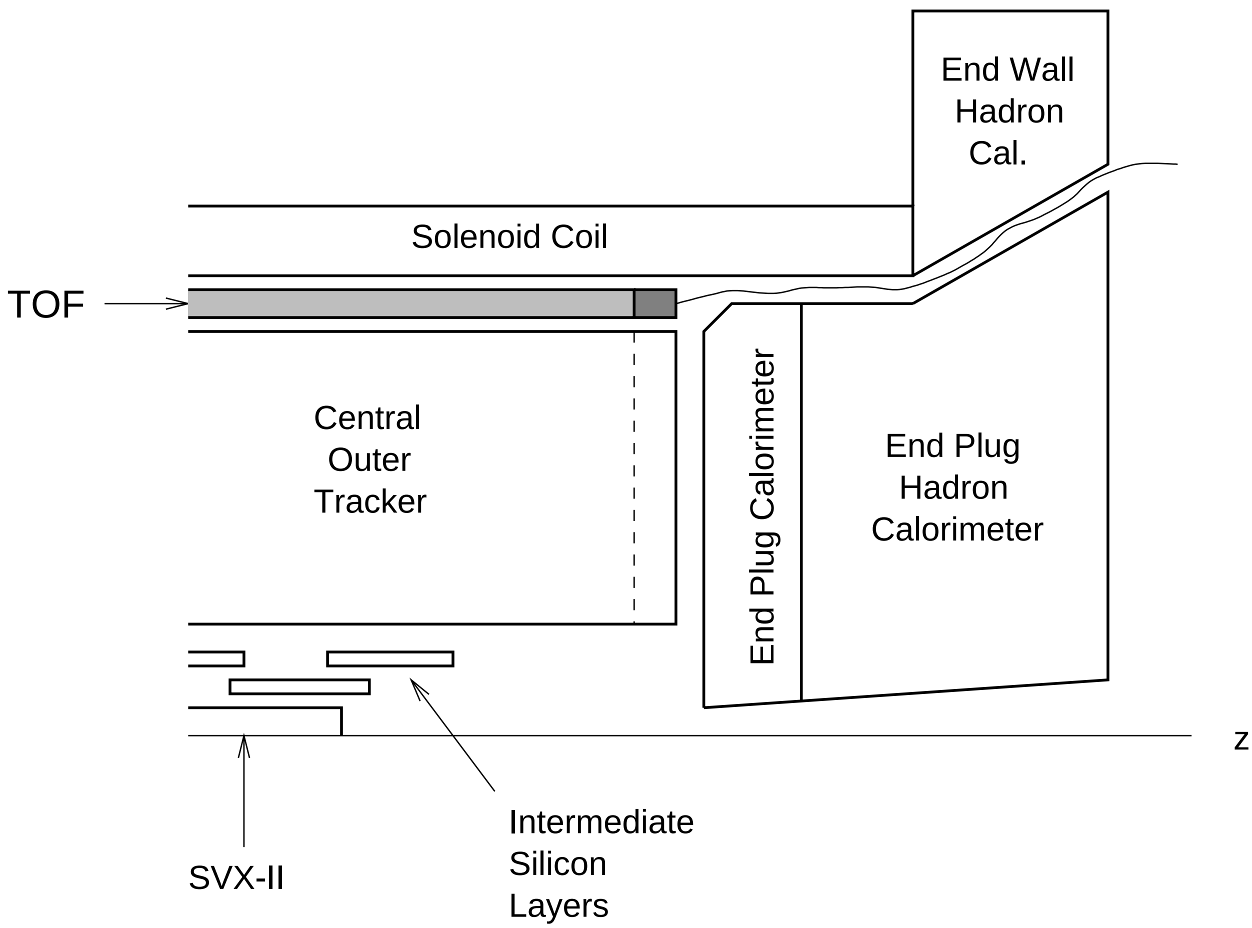
BTeV (Fermilab Tevatron)

- Two-arm spectrometer in colliding beam
- lepton and displaced track trigger at first level

LHC-b (CERN)

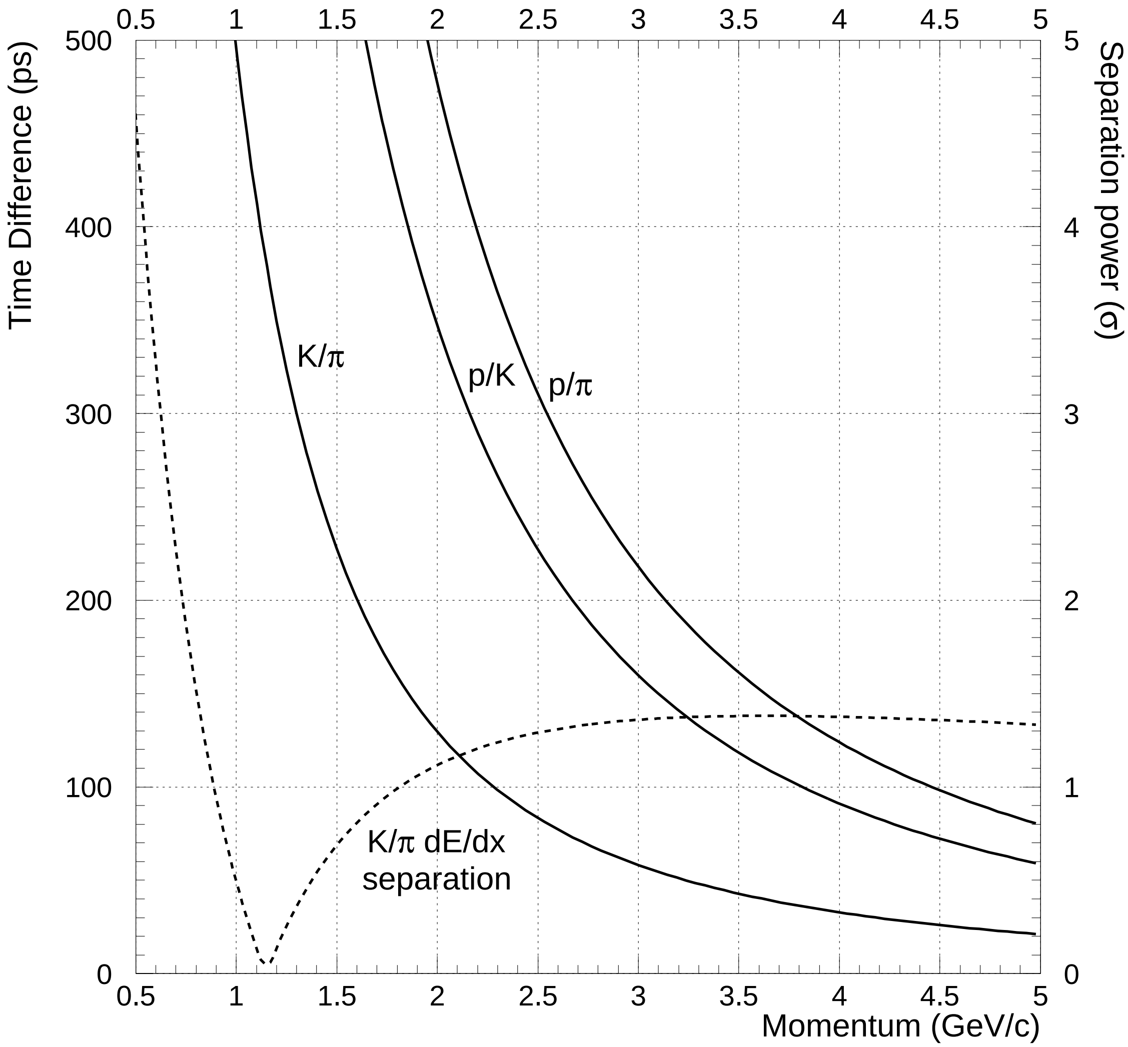
- one-arm spectrometer in colliding beam
- lepton and high-p_T hadron trigger at first level
  displaced track trigger at second level

A Time-of-Flight Detector for CDF



- 216 scintillator bars located just outside COT
  - 3m long
  - cross-section $\approx 4 \times 4\text{cm}^2$
  - read out on both ends with fine-mesh PMTs
- Expected time-of-flight resolution: 100ps
- Primary purpose: kaon identification for B hadron flavor determination

Particle Identification with TOF



With 100ps resolution: 2σ separation of

- K and π for $p < 1.6$ GeV$/c$
- p and K for $p < 2.7$ GeV$/c$
- p and π for $p < 3.2$ GeV$/c$

TOF and dE/dx are complementary