B-Physics at CDF

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B Hadron Production:

- total and differential cross sections

B Hadron Spectroscopy:

- B^+, B^0, B_s, B_c^+, Λ_B masses

B Hadron Decays:

- Branching ratios
- Rare Decays
- Polarization
- Lifetimes

B Meson Flavor Oscillation:

- Time integrated and Time dependent
- Flavor tagging

CP Violation in *B* Meson system:

- $\sin 2\beta$

Over 40 *B*-Physics publications in Run I

☆ Excellent prospects for Run II ☆

B Physics at CDF in Run I

Compare $\sigma(b\bar{b})$:

- $\Upsilon(4S)$ $\approx$1 nb (only B^0, B^+)
- Z^0 $\approx$7 nb
- $p\bar{p}$ $\approx$100 μb

Light quark σ(inelastic) 10^3 larger

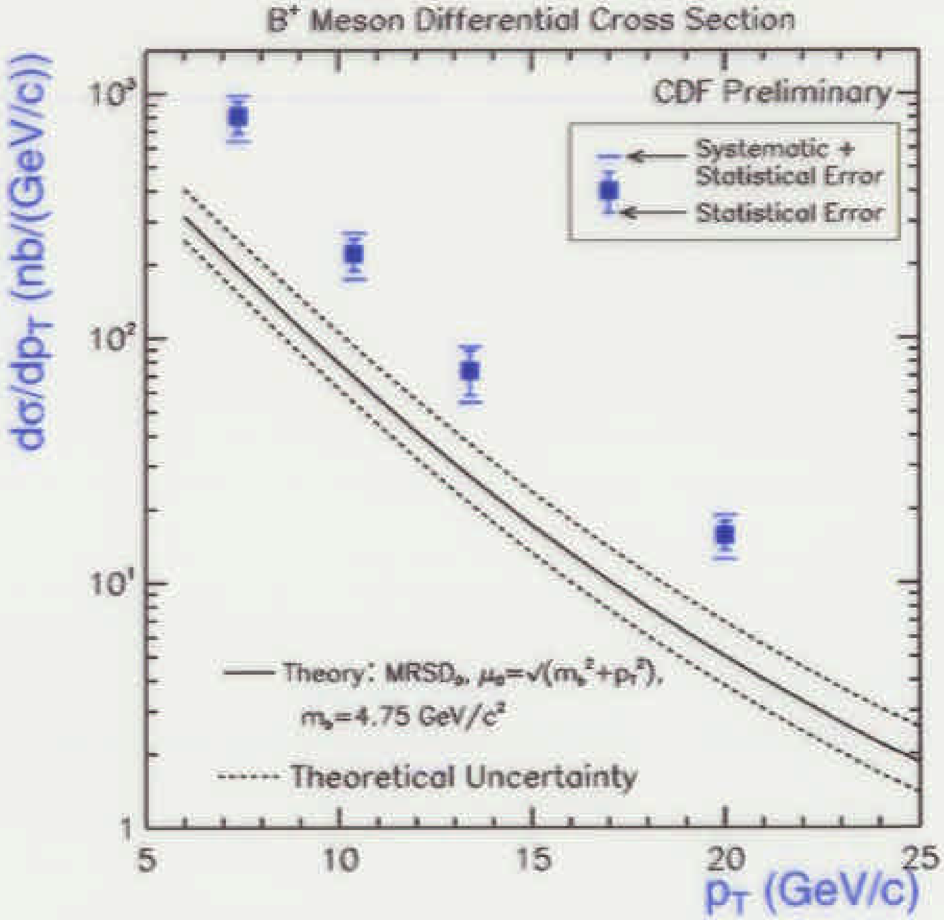
B-hadron triggers required

CDF Run I

- $\mathcal{L} = 110\ pb^{-1}$ at $\sqrt{s} = 1.8$ TeV
- Lepton (e, μ) triggers
  - inclusive, $p_T(B) \approx 20$ GeV
  - dileptons, $p_T(B) \approx 10$ GeV

CDF Run II

- $\mathcal{L} = 2\ fb^{-1}$ at $\sqrt{s} = 2.0$ TeV
- displaced vertex triggers



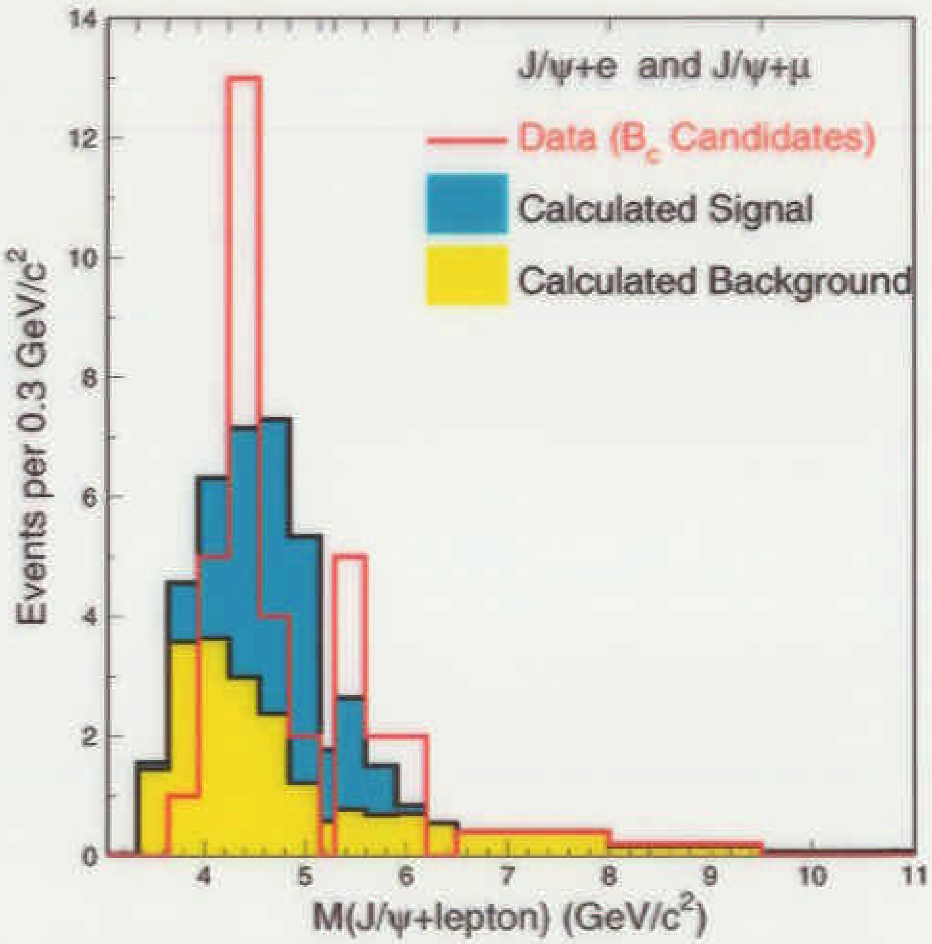
$\sigma_{B^0}(p_T(B^0) > 6\ GeV;\ |y| < 1) =$

$3.51 \pm 0.42(stat) \pm 0.53(syst)\ \mu b$

Highlights: *B* Hadron Masses

B-hadron masses [MeV/c^2]

- B^+ mass:
  - ☆ 5279.1 ± 1.7 ± 1.4
  - ☆ 5279.1 ± 0.4 ± 0.4 (CLEO)
- B^0 mass:
  - ☆ 5281.3 ± 2.2 ± 1.4
  - ☆ 5279.1 ± 0.7 ± 0.3 (CLEO)
- B_s mass:
  - ☆ 5369.9 ± 2.3 ± 1.3
  - ☆ 5368.6 ± 5.6 ± 1.5 (ALEPH)
- Λ_B mass:
  - ☆ 5621 ± 4 ± 3
  - ☆ 5621 ± 17 ± 15 (ALEPH)
  - ☆ 5956 ± 22 ± 6 (DELPHI)
- B_c^+ mass:
  - ☆ 6400 ± 390 ± 130



- Decay: $B_c^- \to \bar{\nu}_\ell \ell^- J/\psi X$
  with $J/\psi \to \mu^+\mu^-$
- Number of events: $20.4^{+6.2}_{-5.5}$

B Hadron Lifetimes at CDF

Why measure *B* lifetimes?

- extract $|V_{cb}|$ using $1/\Gamma$
- lifetimes the same at 0^{th} order for all *B* hadrons
  - ☆ test heavy quark expansion
- $\Delta\Gamma$ of CP eigenstates
  - ☆ potential for new physics

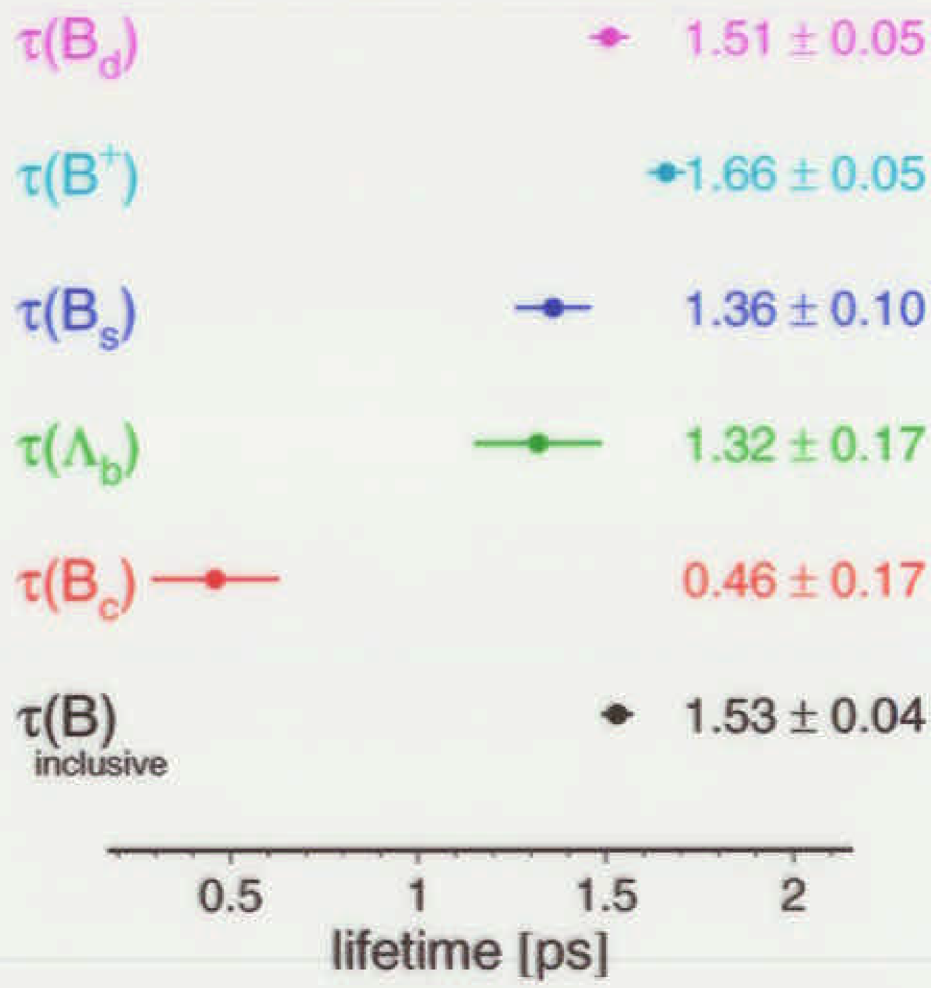
For CP eigenstates

- $\Delta\Gamma$ for $B^0 \approx 1\%$ difficult
- $\Delta\Gamma$ for B_s could be 10 – 20%

CDF measures in $B_s \to \overline{\nu}_\ell \ell^+ D_s^-$:

- $\tau(B_s) = 1.36 \pm 0.09 ^{+0.06}_{-0.05}$ ps
- $\Delta\Gamma/\Gamma(B_s) < 0.83$ at 95% CL

CDF Lifetimes Summary



- Ratio: $\tau(B^+)/\tau(B^0) = 1.09 \pm 0.05$

B Physics and the CKM Matrix

Weak eigenstates ≠ mass eigenstates

Quark mixing described by unitarity CKM[1] matrix:

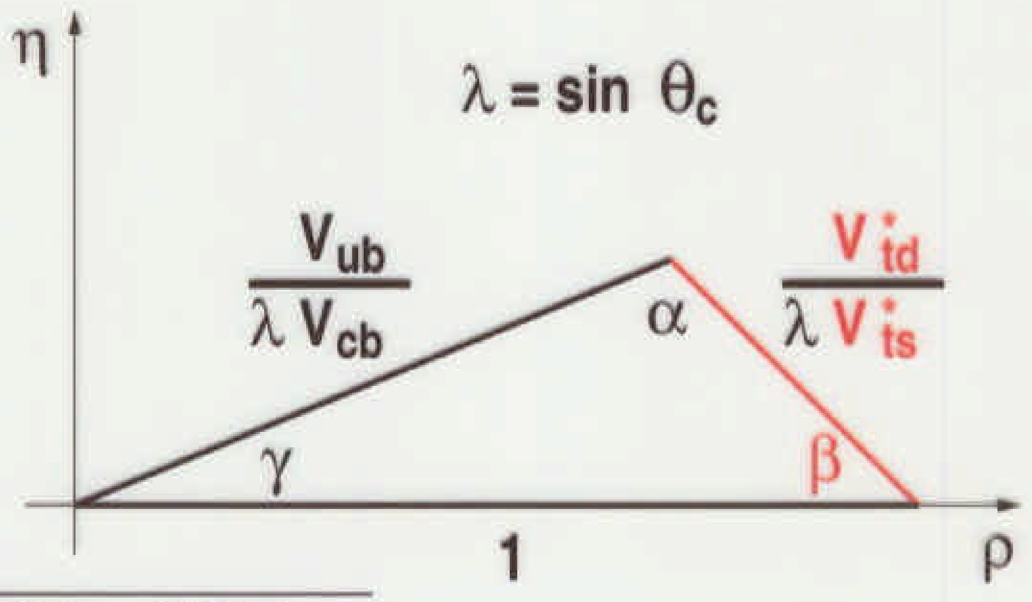
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity implies: matrix has a complex phase

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein Parameterization

$\eta \neq 0$ means CP is violated

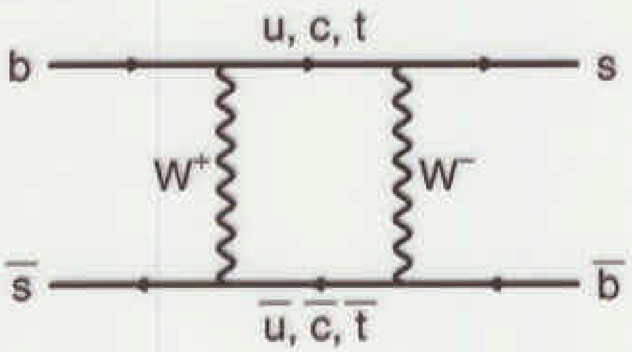


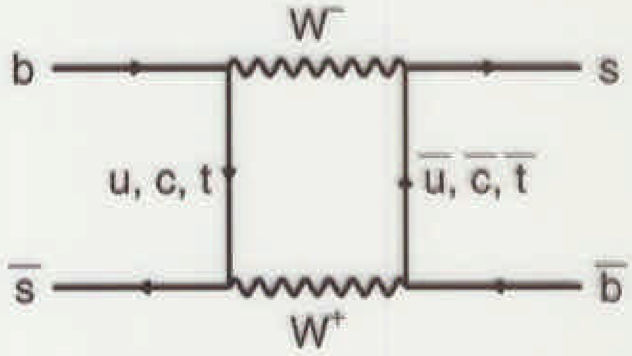
[1] Cabbibo-Kobayashi-Maskawa

CKM Matrix and CP Violation

Mixing depends on CKM matrix

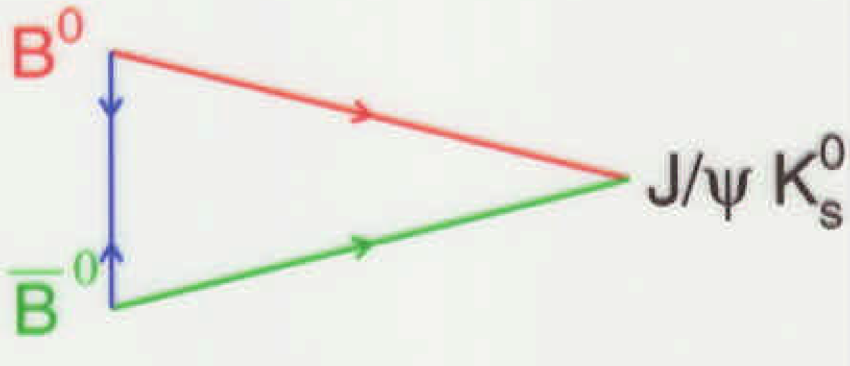
$\Delta m_s \propto |V_{tb}^* V_{ts}|^2$; $\Delta m_d \propto |V_{tb}^* V_{td}|^2$;





CP violation in $B^0 \to J/\psi K^0_S$

- ☞ $J/\psi K^0_S$ is a CP eigenstate
- ☞ $\Gamma(B^0 \to J/\psi K^0_S) \neq \Gamma(\overline{B^0} \to J/\psi K^0_S)$



CP violation in interference of mixing and decay

$A(B^0 \to \overline{B^0}) \propto |A|\, e^{i2\beta}$; $A(\overline{B^0} \to B^0) \propto |A|\, e^{-i2\beta}$;

Experimental Aspects

Measure

- proper decay time, ct (B_s rest frame)
- B_s flavor at decay (final state)
- B_s flavor at production (flavor tag)

Measured time dependent asymmetry

$$A_0(t)_{(meas)} \equiv \frac{N(t)_{RS} - N(t)_{WS}}{N(t)_{RS} + N(t)_{WS}} = D\cos(\Delta m_s\, t)$$

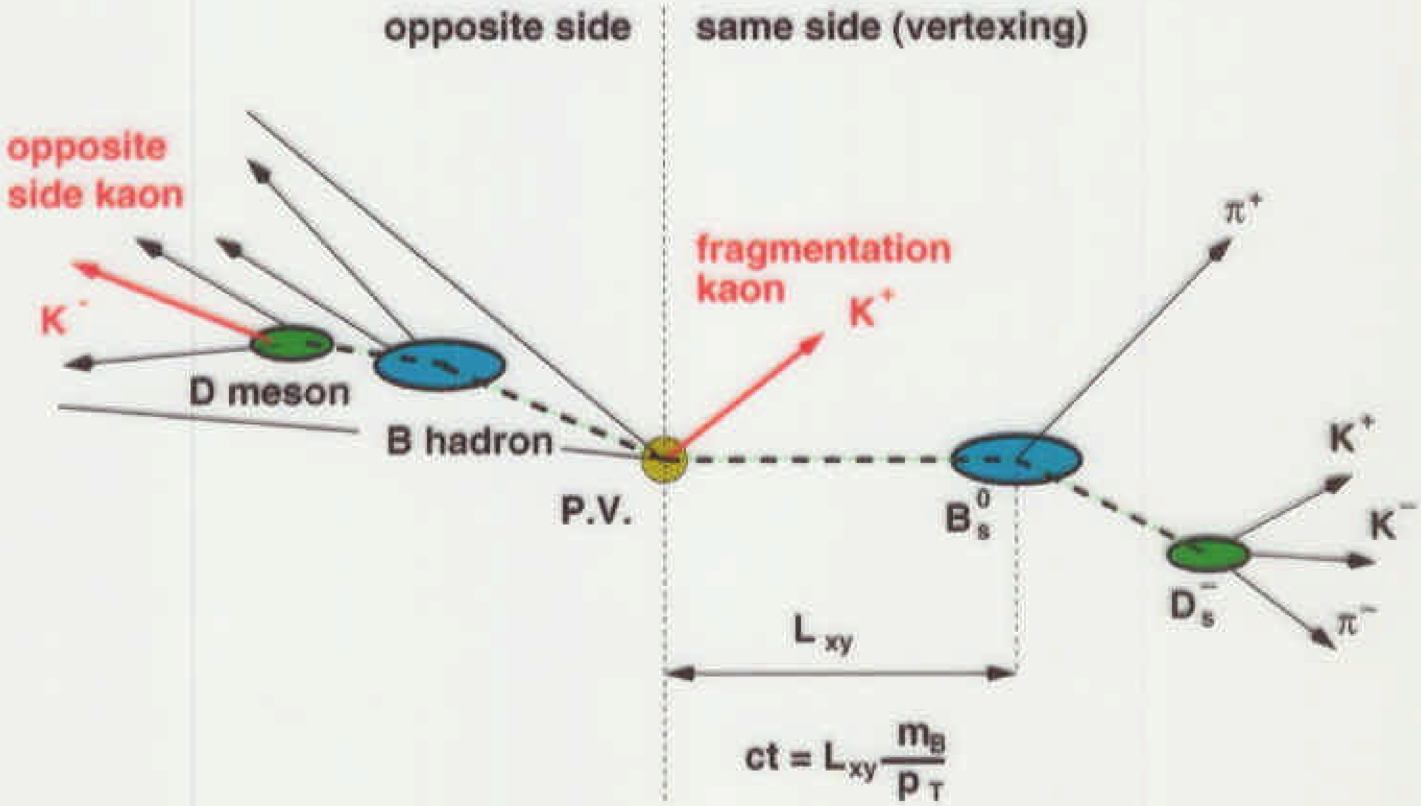


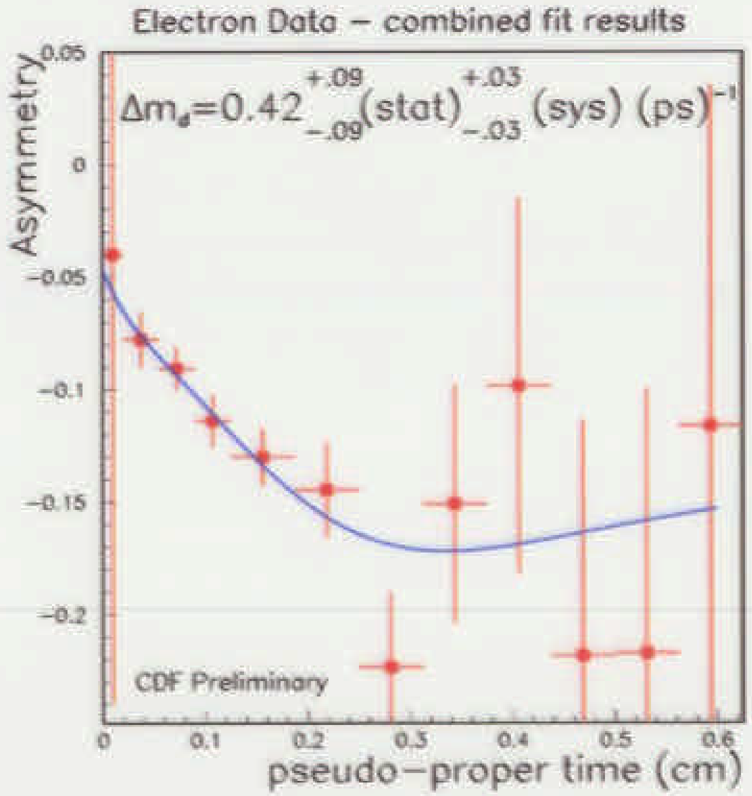
Figure of merit for tagger:

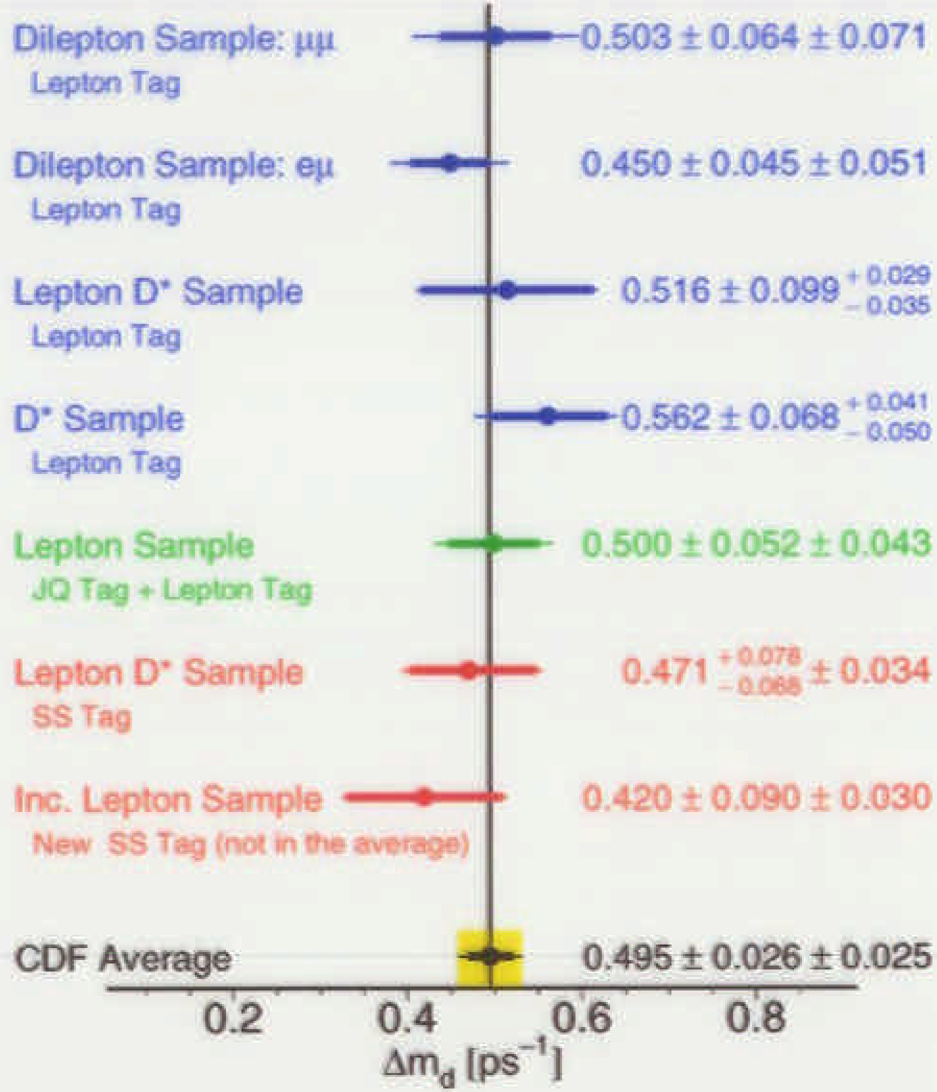
εD^2; equivalent to the effective event statistic

B^0 Mixing Measurements

New preliminary measurement

- inclusive lepton (e, μ) sample
- same side tagger (fragm. π)
- crucial: avoid tag on B daughters
- same side tagger re-tuned

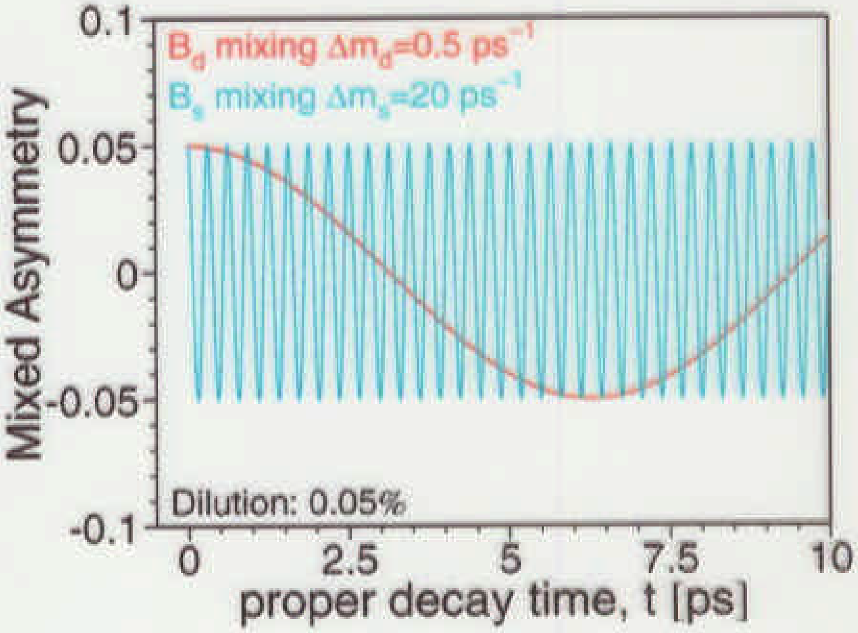


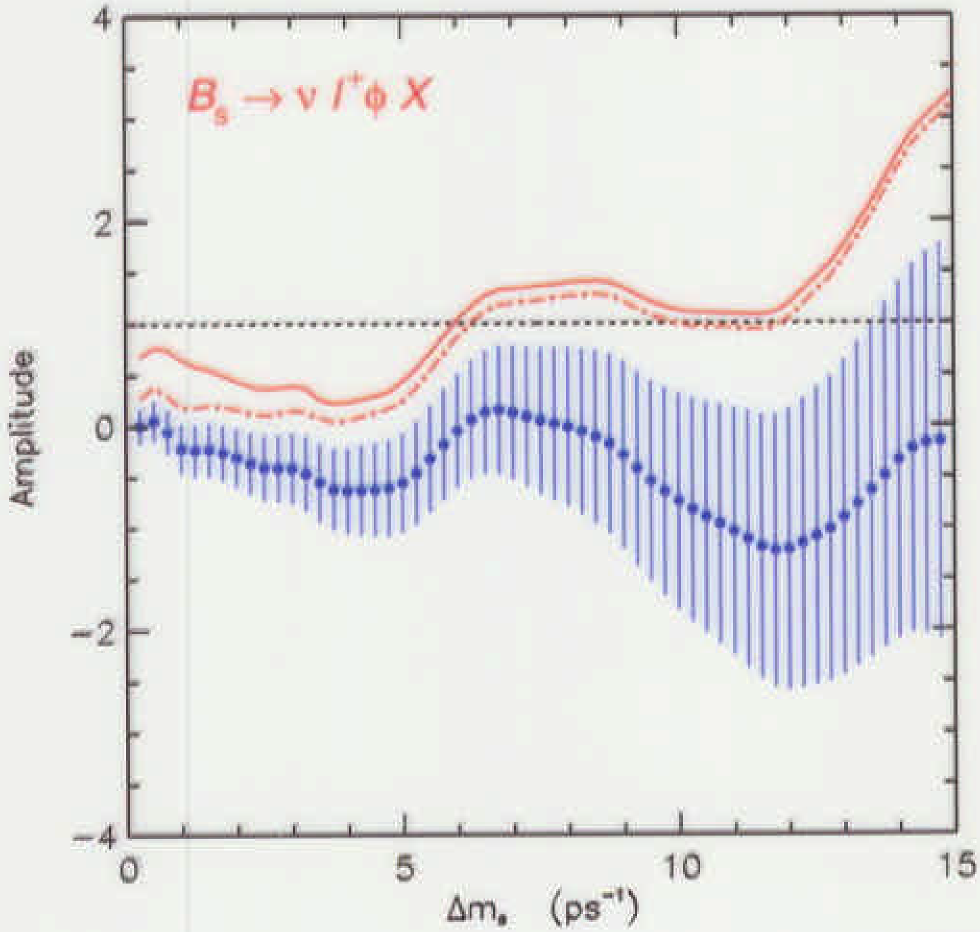


B_s Mixing Limit

Search B_s mixing in $B_s \to \nu_\ell \ell^+ \phi X$

- tagging as in B^0
- opposite side tag
- soft lepton
- neutrino lost
- ct resolution





Limit on Δm_s:

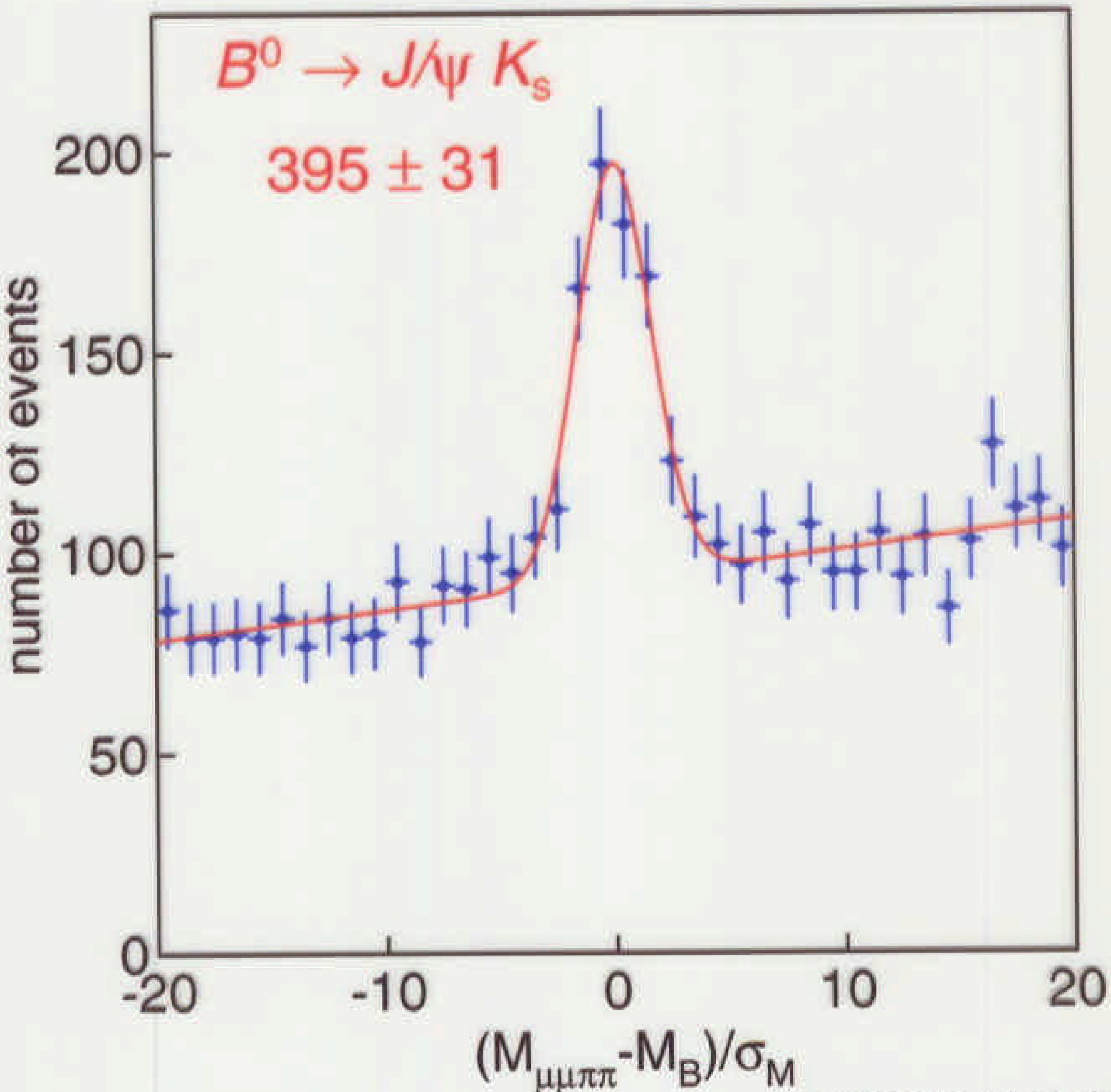
$\Delta m_s > 5.8 ps^{-1}$

at 95% C.L.

Signal $B^0 \to J/\psi K^0_S$ for $\sin 2\beta$

Event sample:

- events with both μ in silicon detector
  - ☆ precise proper time measurement
- at most one μ in silicon detector
  - ☆ less precise proper time measurement
- tagging dilution from $B^+ \to J/\psi K^+$

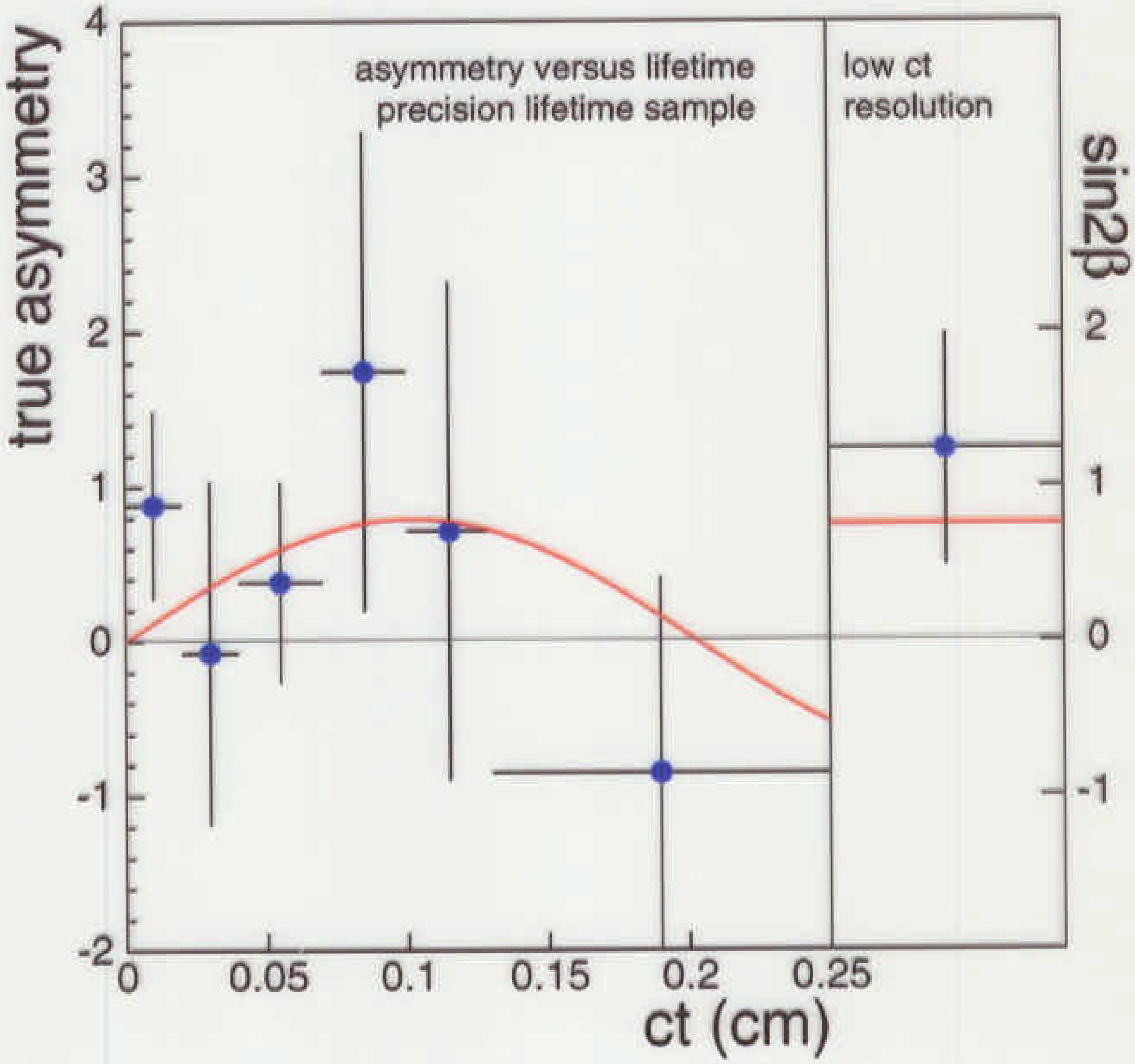


Summary: $\sin 2\beta$ in $B^0 \to J/\psi K^0_S$

Same side π, jet charge and soft lepton

$\sin 2\beta = 0.79^{+0.41}_{-0.44}$ $\varepsilon D^2 = 6.3 \pm 1.7\%$

first presented 1999 now published: PRD 61, 072005 (2000)



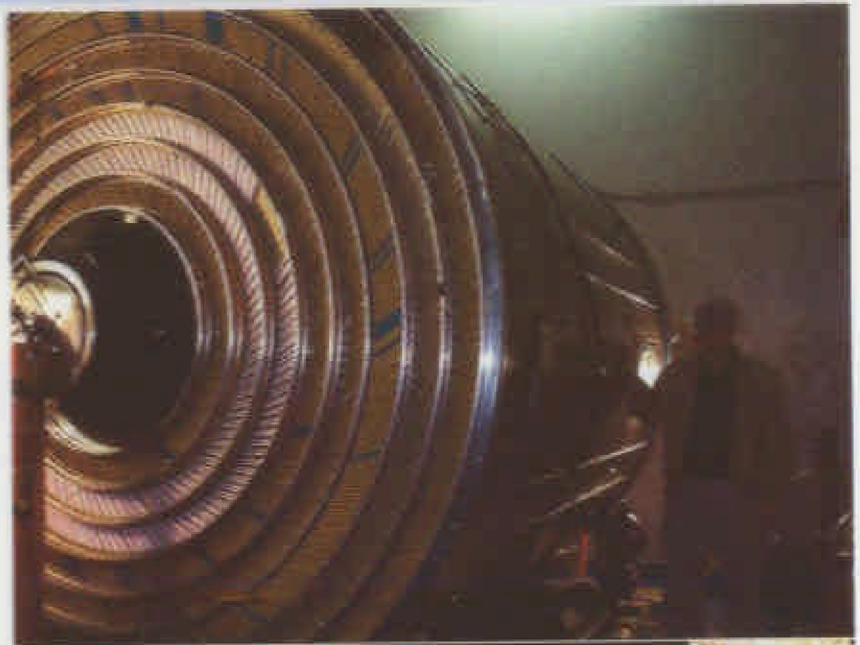
Run II B Physics Highlight

CDF Detector Upgrades

- new silicon tracker, (acc. $\times$ 1.4)
  - r-z and r-ϕ measurements
- new dead-time-less DAQ system
  - track trigger at L1
  - displaced vertex trigger at L2
  - purely hadronic trigger possible
- Time-of-Flight system
  - $p < 1.6$ GeV: 2 σ K/π separation
  - roughly doubles εD^2 for B_s

CDF Detector Upgrade Status

- commissioning run, Sept. 2000
- run starts March 2001
- new central tracker installed
- Time-of-Flight system installed
- silicon detectors well on schedule



Run II B Physics Highlights

CDF Run II

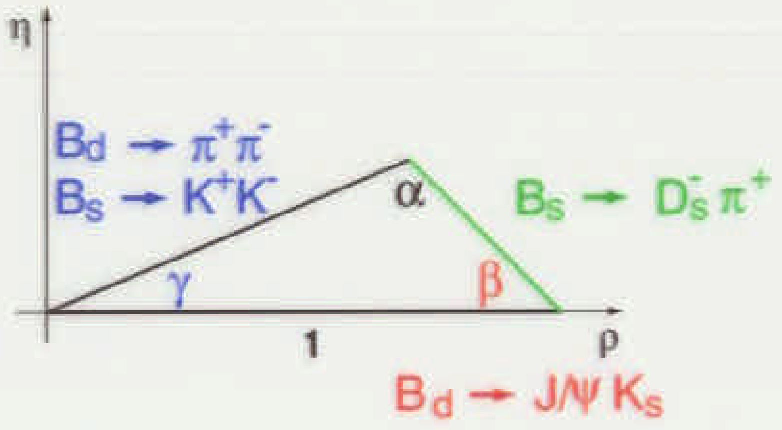
- $\mathcal{L} = 2\ fb^{-1}$ at $\sqrt{s} = 2.0$ TeV
- displaced vertex triggers

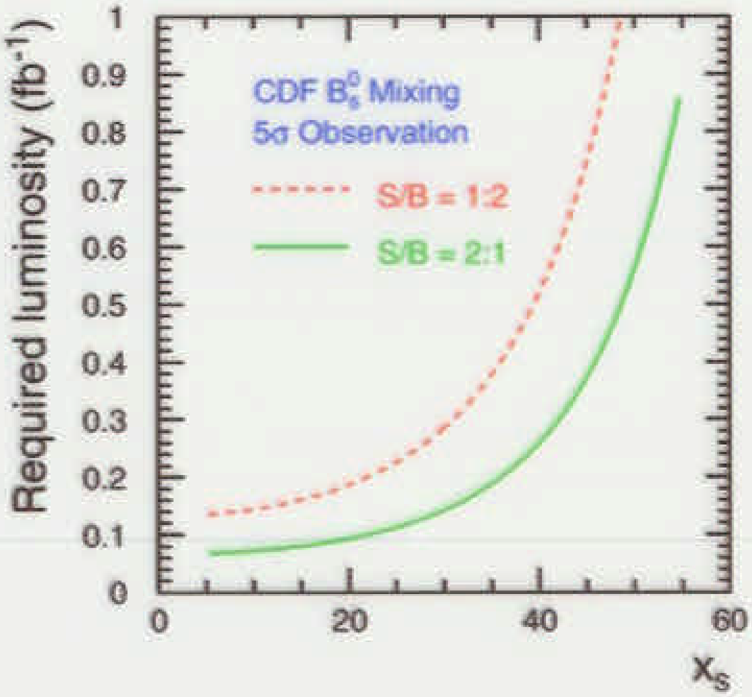
CP violation

- $\sin 2\beta$ in $B^0 \to J/\psi K^0_S$
  - ☆ events: $\approx 10{,}000$
  - ☆ error: $\sigma(\sin 2\beta) \approx 0.072$
- γ in $B^0 \to \pi^- \pi^+ / B_s \to K^- K^+$
  assume: $S/B = 1/2$; $\Delta m_s = 30\ ps^{-1}$
  - ☆ events: $\approx 5{,}000 / \approx 10{,}000$
  - ☆ error: $\sigma(\gamma) \approx 7^o$

B_s physics

- mixing in $B_s \to D_s^- \pi^+$
  - ☆ sensitivity up to $x_s \approx 65$
- $\Delta\Gamma_s$ in $B_s \to J/\psi\ \phi$
  - ☆ error $\sigma(\Delta\Gamma_s/\Gamma) \approx 0.05$





Summary and Conclusions

B Physics Results from Run I

- rich physics harvest from Run I
- masses, lifetimes, mixing ....
- first observation of B_c
- first $\sin 2\beta$ measurement

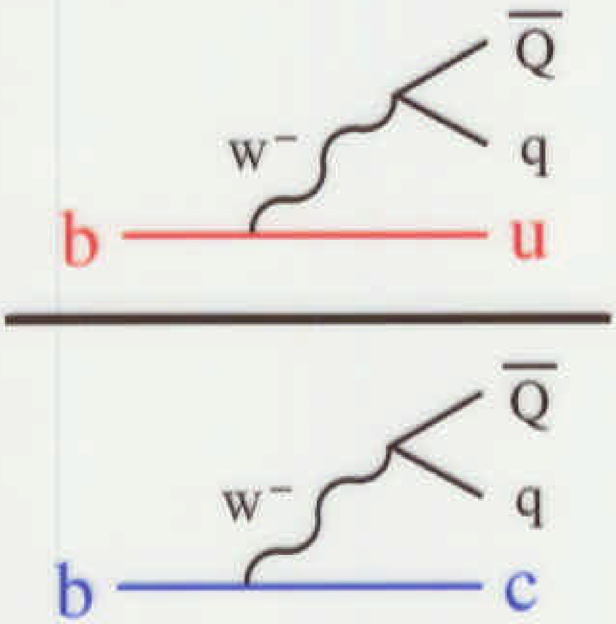
B Physics Prospects for Run II

- constrain unitarity triangle
- probe the CKM sector for new physics
- measure $\sin 2\beta$
- measure angle γ
- measure one side with B_s mixing
- Run I, measurements with more statistics
- and much more ....

Incredibly rich B-Physics program and

... lots of fun at CDF

Measuring γ: The Idea



$$\propto \left|\frac{V_{ub}}{V_{cb}}\right| e^{i\gamma}$$

Expect 100 evts: $B^+ \to D^0 K^+$

Atwood,Soni,Dunietz PRL 78 (1997) 3257

Strategy: $B_s \to K^- K^+$ / $B^0 \to \pi^- \pi^+$

	$\bar{A}/A$	$Im(\frac{\bar{A}M_{12}^*}{A\lvert M_{12}\rvert})$
$B^0 \to \pi^- \pi^+$	2γ	$\sin 2(\gamma + \beta + \phi_{NP}^d)$
$B_s \to K^+ K^-$	2γ	$\sin 2(\gamma + \phi_{NP}^s)$

But careful: penguins are large

Measuring γ for Real

Four parameters

Fleischer PLB 459 (1999) 306

- d = ratio of hadronic matrix elements "P/T"
- θ = phase of above d
- γ, β = weak phases

Five observables

$$
\begin{aligned}
A_{cp}(t) &= A_{cp}^{dir} \times \cos \Delta m t + A_{cp}^{mix} \times \sin \Delta m t \\
A_{cp}^{dir}(\pi^+\pi^-) &= -\frac{2d \sin\theta \sin\gamma}{1-2d\cos\theta\cos\gamma+d^2} \\
A_{cp}^{dir}(K^+K^-) &= \frac{2d\frac{1-\lambda^2}{\lambda^2}\sin\theta\sin\gamma}{1+2d\frac{1-\lambda^2}{\lambda^2}\cos\theta\cos\gamma+(\frac{1-\lambda^2}{\lambda^2})^2 d^2} \\
A_{cp}^{mix}(K^+K^-) &= \frac{\sin 2\gamma+2d\frac{1-\lambda^2}{\lambda^2}\cos\theta\sin\gamma}{1+2d\frac{1-\lambda^2}{\lambda^2}\cos\theta\cos\gamma+d^2(\frac{1-\lambda^2}{\lambda^2})^2} \\
A_{cp}^{mix}(\pi^+\pi^-) &= \frac{\sin 2(\beta+\gamma)-2d\cos\theta\sin(2\beta+\gamma)+d^2\sin 2\beta}{1-2d\cos\theta\cos\gamma+d^2} \\
A_{cp}^{mix}(J/\psi K_s) &= \sin 2\beta
\end{aligned}
$$

Assume: $S/B = 1/2$; $\Delta m_s = 30\ ps^{-1}$

Results

$\sigma(A_{cp}(B_s \to K^- K^+)) \approx 0.08$, $\sigma(A_{cp}(B^0 \to \pi^- \pi^+)) \approx 0.14$

$\sigma(\gamma) \approx ^{+5.4^o}_{-6.8^o}$ (*stat*) $\pm 3^o$ (*syst*)

systematics: 20% SU(3) breaking