B-Physics Results from the Fermilab Tevatron

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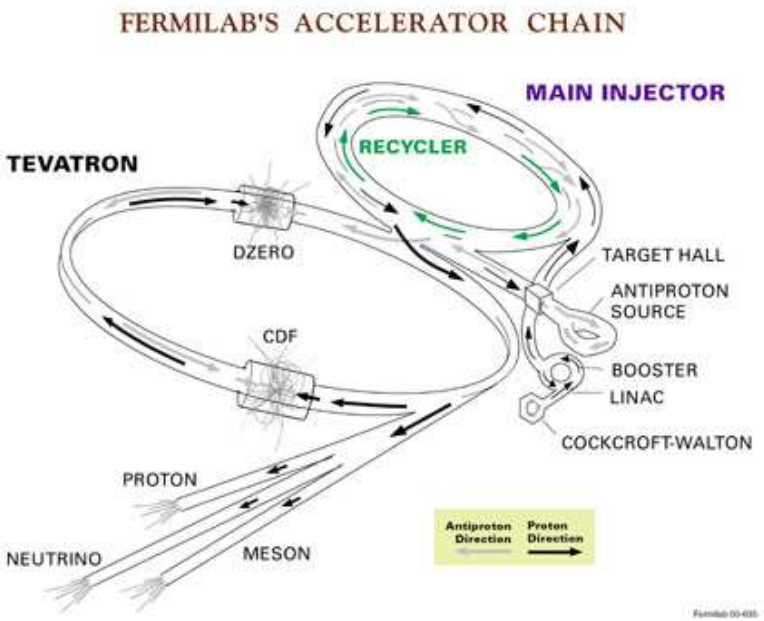
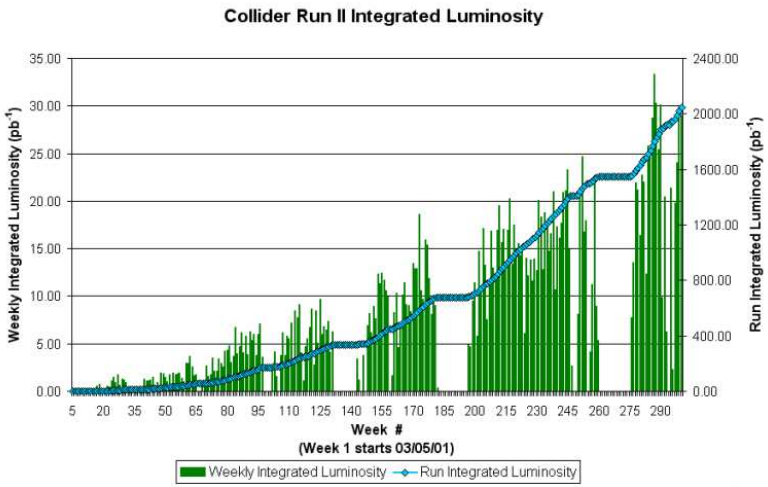
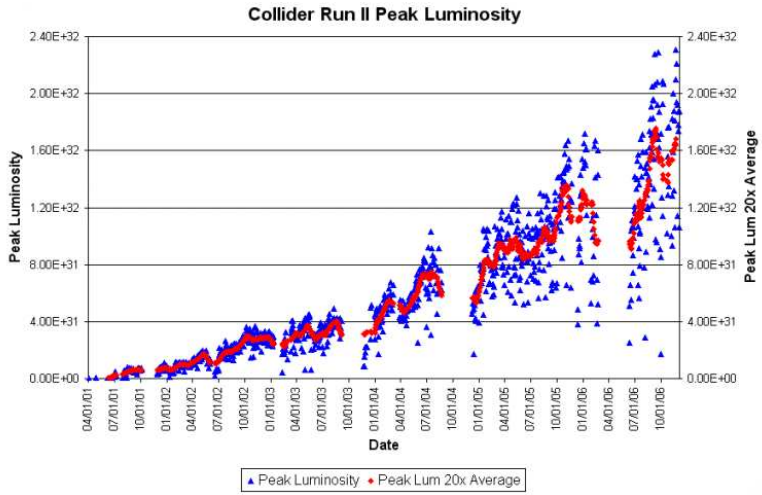
Tevatron B-Physics—Overview

- Run II B-Physics results
  - Lifetime (B^+, B_d^0, B_s^0, B_c^+, Λ_B, ...) measurements
  - Mixing (B_d^0, B_s^0) measurements
  - Branching ratios ($B_{(s)}^0 \to \mu^+\mu^- X$, $B_s^0 \to D_s \bar{D}_s$ ...)
  - Spectroscopy (B_c, B_1, B_2^*, B_{s2}^{*0}, ...)
  - Production properties (cross sections, etc.)
- This presentation will focus on B_s system
  - Mixing: Δm_s
  - Lifetime difference: $\Delta\Gamma_s$ and ϕ_s
  - Mixing-induced CP violation: A_{SL}^s
  - Direct CP violation: $A_{CP}(B_s \to K^-\pi^+)$

The Tevatron

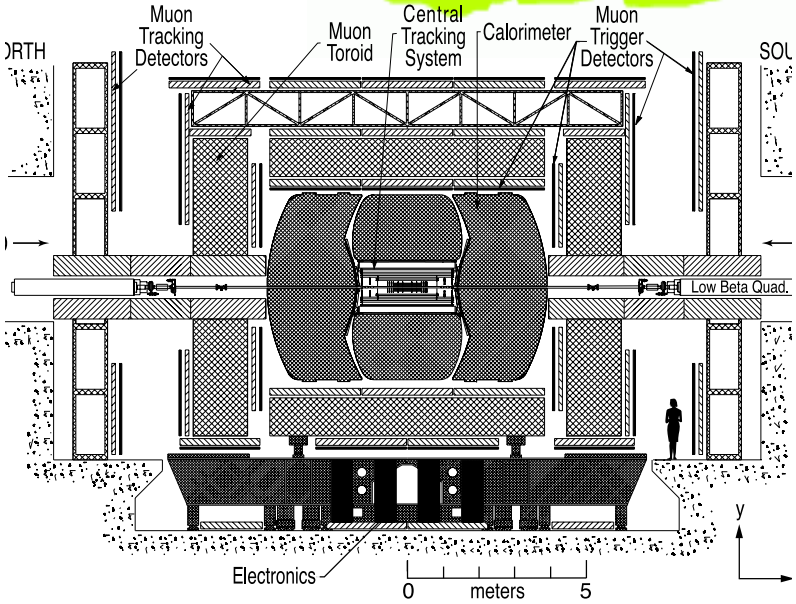






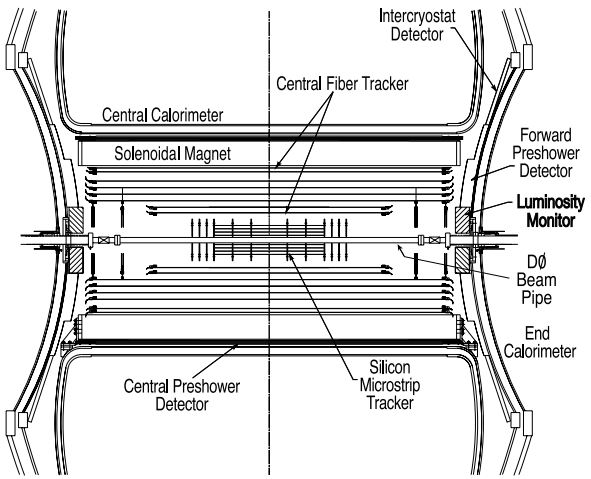
- $p\bar{p}$ @ $\sqrt{s} = 1.96$ TeV
- $\sigma(p\bar{p} \to b\bar{b} + X) \approx 150\ \mu$b
  B-Factories $\sigma \approx 1$ nb
- Results: $\int \mathcal{L}\, dt = 1$ to 1.3 fb^{-1}

DØ Detector

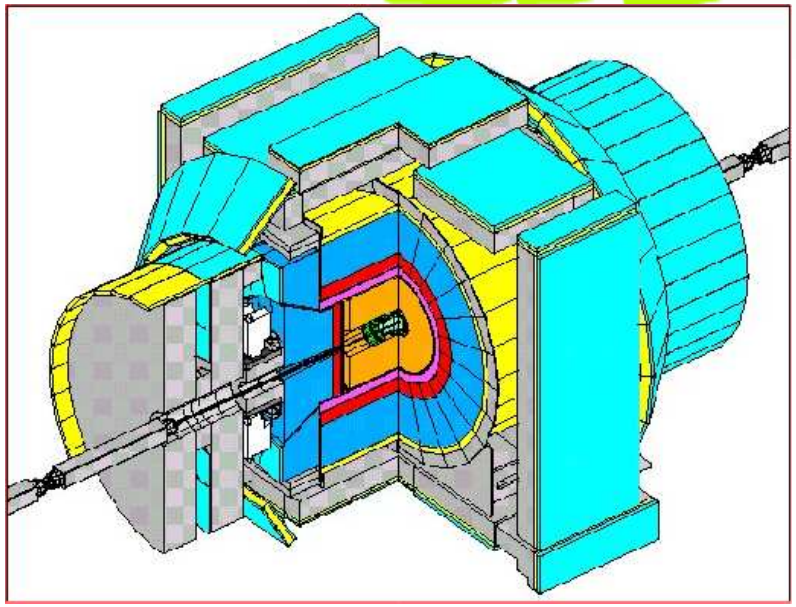


- DØ triggers on muons
- Large muon acceptance
- Silicon vertex detector—*recently added additional inner layer* (L0)

- Tracker radius: 0.5 m
- Solenoid B-Field: 2 T
- Without L0: $\delta p_T/p_T = 0.024\, p_T$
- With L0: $\delta p_T/p_T = 0.0215\, p_T$



CDF Detector



- Tracker radius: 1.0 m
- Solenoid B-Field: 2 T
- p_T resolution: $\frac{\delta p_T}{p_T} = 0.0015\, p_T$
- Particle ID: $\frac{dE}{dx}$ & TOF

- Level 1 track trigger
- Level 2 impact parameter and secondary vertex trigger
- Trigger on both leptonic and hadronic modes

The B_s System

- Time evolution of B_s (Flavor Eigenstates)

$$-i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}=\left(\mathbf{M}+\frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}$$

$CPT \Rightarrow M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$

Hermiticity $\Rightarrow M_{12}=M_{21}^*$ and $\Gamma_{12}=\Gamma_{21}^*$

- Mass eigenstates (equal CP eigenstates if $q/p=1$)

$$|B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$
$$|B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$

CP violation in mixing if $|q/p|\neq 1$

Mixing—Overview

- Since Mass and Flavor eigenstates not equal, flavor states can mix.
  - Requires mass of eigenstates to differ $(\Delta m_q \neq 0)$
  - Mass eigenstates can have different lifetimes $(\Delta\Gamma_q \neq 0)$
  - Standard Model expectation $\Delta m_q \gg \Delta\Gamma_q$

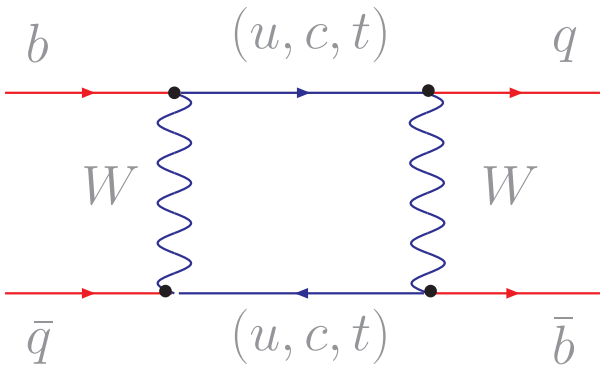
$$\mathcal{P}^{\text{unmixed}}_{\text{mixed}}(t) = \frac{1}{2}\Gamma_q\, e^{-\frac{\Gamma_q}{2}t}\left[\cosh\left(\frac{\Delta\Gamma_q}{2}t\right) \pm \cos\left(\Delta m_q t\right)\right]$$

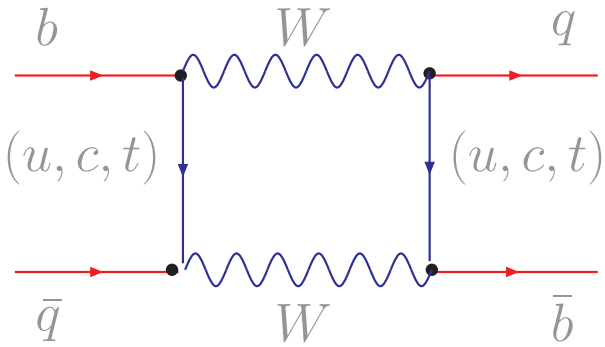
where $\Gamma_q = \frac{\Gamma_H + \Gamma_L}{2}$ the average of the decay widths of the two mass eigenstates.

  - Exp. gives $\Delta\Gamma_q \ll \Delta m_s$ which implies $|\Gamma_{12}| \ll |M_{12}|$ then $\Delta m_s \approx 2|M_{12}|$ & $\Delta\Gamma_s \approx 2|\Gamma_{12}|\cos\phi_s = \Delta\Gamma_{CP}\cos\phi_s$

Mixing—Overview

- Mixing requires a $|\Delta B| = 2$ transition $(B^0 \to \bar{B}^0)$

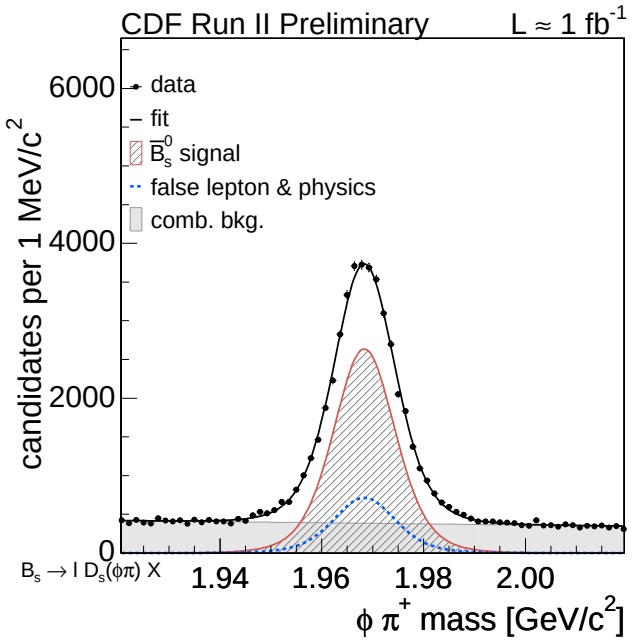


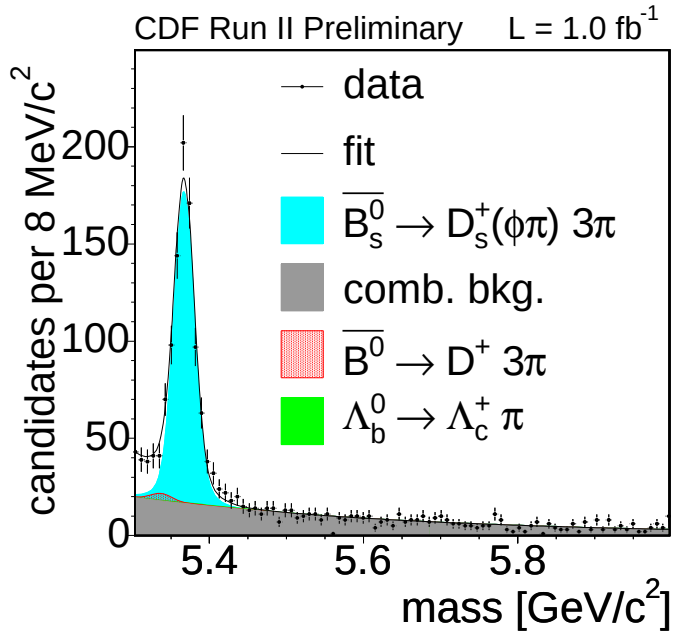


- Amplitude is $\propto |V_{tb}V_{tq}|$ because of large t-quark mass
  - Amplitude $\propto \sum_q S_0\left(\frac{m_q}{M_W}\right)$

Mixing—Event Sample

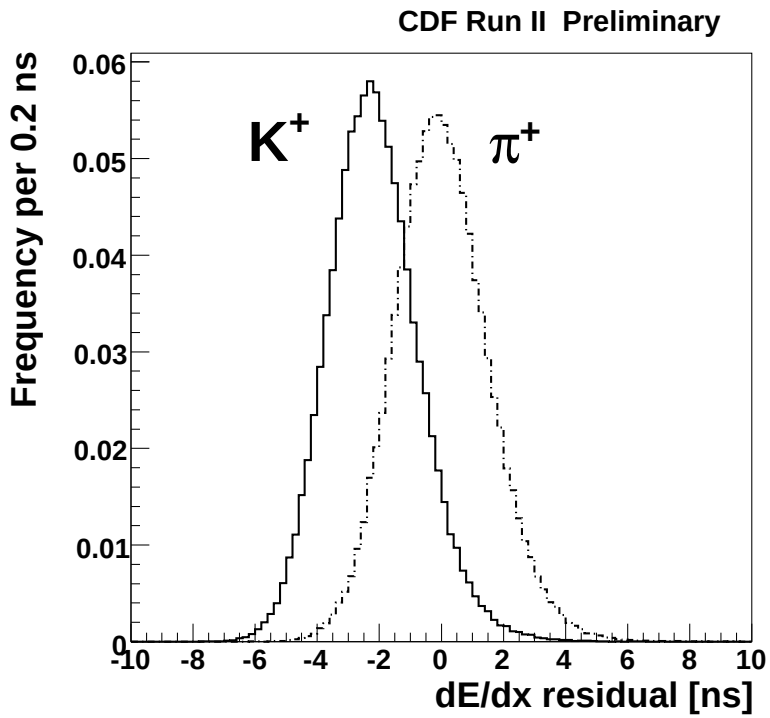
- Hadronic (CDF) and Semileptonic (CDF & DØ) samples
  - Start by selecting $D_s^+ \to \phi(K^+K^-)\pi^+,\ K^{*0}K^+,\ \pi^+\pi^-\pi^+$
- Hadronic sample (8700): $B_s^0 \to D_s^+\pi^-,\ D_s^+\pi^-\pi^+\pi^-$
  - Selection uses ANN & kaon-id (TOF & dE/dx)





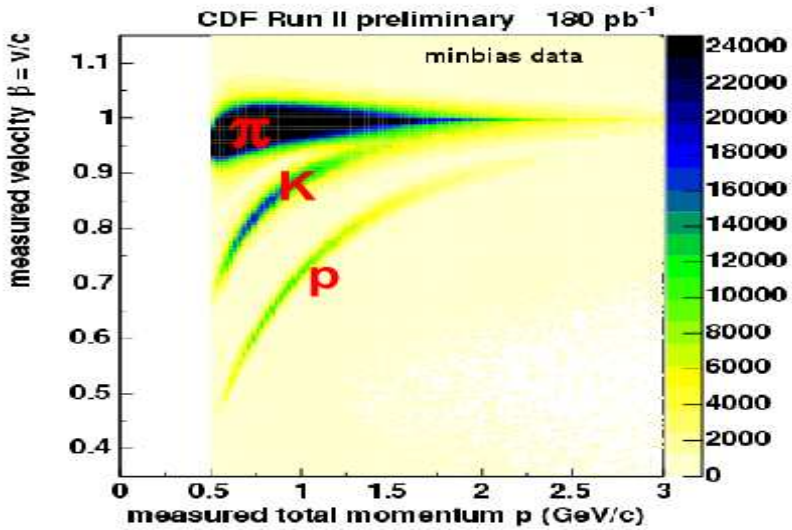
Mixing—Particle ID

dE/dx in Drift Chamber



K/π **separation** $> 1.5\sigma$ @ $p_T > 2$ **GeV**

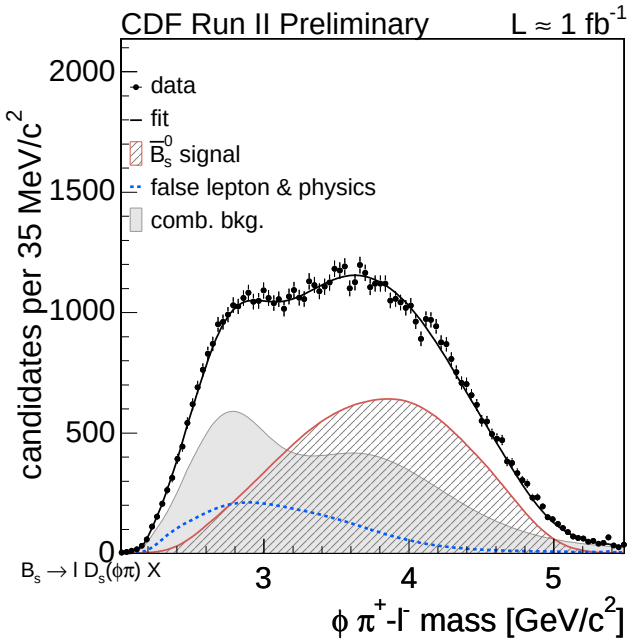
Time of Flight (TOF)



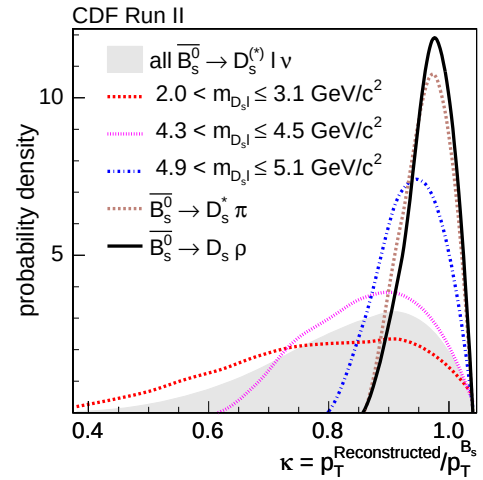
$> 1\sigma$ K/π **Separation up to** $p = 2$ **GeV**

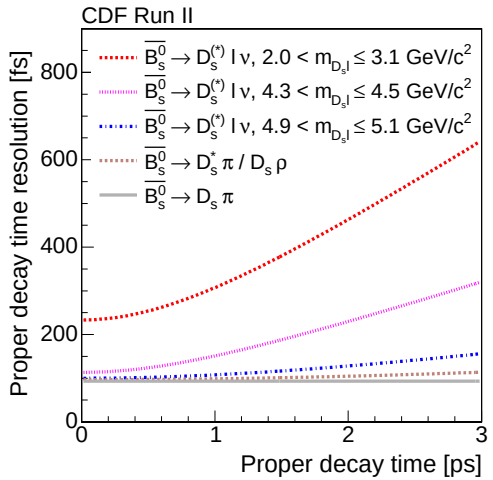
Mixing—Event Sample

- Semileptonic sample (61500):
  $B_s \to D_s^+ \ell^- \bar{\nu}_\ell$ (ℓ is e or μ)



Semileptonic Lifetime



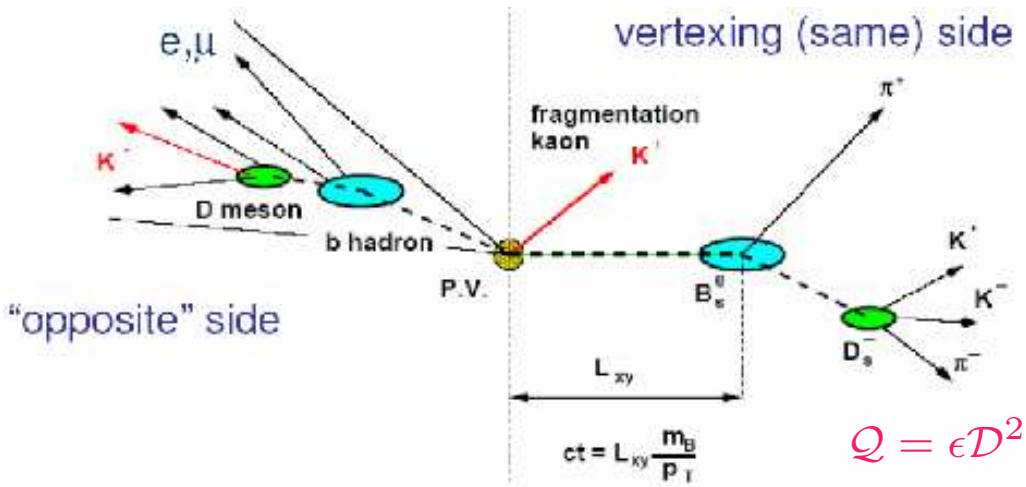


Mixing—Flavor Tagging

- Mixing requires measurement of initial and final state flavors
  - Final state tagging examples

$$B_s^0 \to D_s^+ \mu^- \nu_\mu \qquad\qquad B_s^0 \to D_s^+ \pi^-$$

  - Initial state: opposite or same side charge



Opposite-side Tag (OST): K, ℓ, Jet-charge in NN

Same-side Tag SST: K in NN

$$\mathcal{Q} = \epsilon \mathcal{D}^2 = \begin{cases} 1.8 \pm 0.1\% & \text{comb. OST} \\ 3.7 \pm 0.9\% & \text{semileptonic SST} \\ 4.8 \pm 1.2\% & \text{hadronic SST} \end{cases}$$

B_s Mixing—Results

CDF: ≈ 1 fb^{-1}

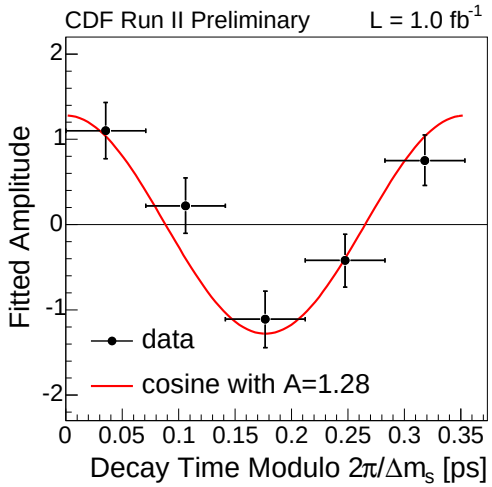
$\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}

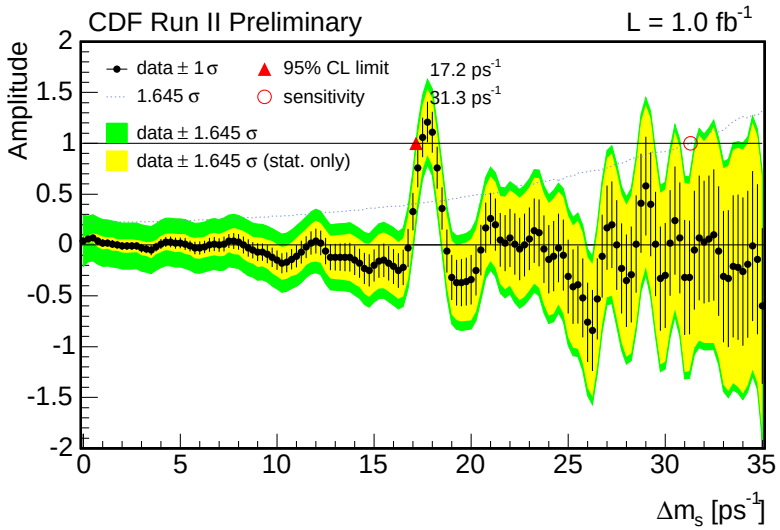
$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$

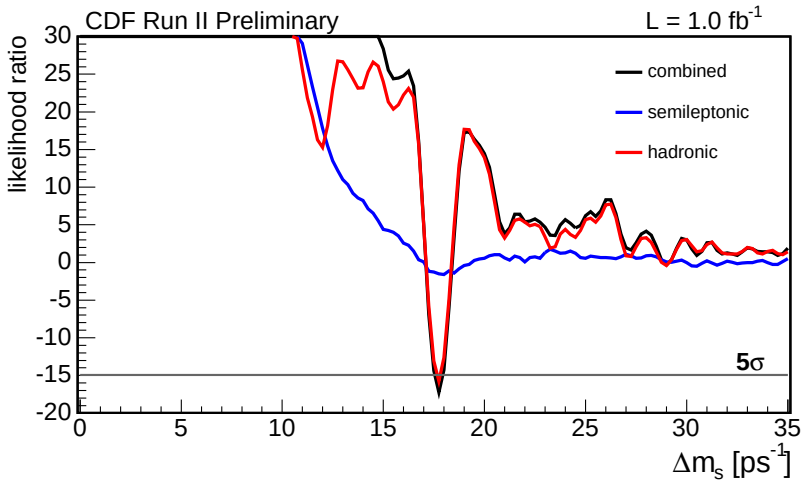
DØ: ≈ 1 fb^{-1}

$17 < \Delta m_s < 21$ ps^{-1} @ 90% CL,

with 19 ps^{-1} most probable value







$\Delta\Gamma_s$—*Overview*

- Presentation concentrates on DØ analysis
- Lifetime of mass eigenstates not expected to be equal
  - $\Delta\Gamma_q/\Gamma_q$ expected to be small, but since $\Delta m_s \gg \Delta m_d$ might expect $\Delta\Gamma_s/\Gamma_s \gg \Delta\Gamma_d/\Gamma_d$
    - SM predictions:

$$\Delta\Gamma_d/\Gamma_d \approx 0.01 \qquad \Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06$$

  - Mixing-induced CP violating phase ($\Delta\Gamma = \Delta\Gamma_{CP}\cos\phi_s$) given by

$$e^{i\phi_s} = \frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}}\frac{V_{cs}^*V_{cb}}{V_{cs}V_{cb}^*} \quad \Rightarrow \quad \phi_s \approx -0.03$$

$\Delta\Gamma_s$—*Analysis*

- Must separate the two mass eigenstates
  - These are the CP even and odd states for small ϕ_s

$$B_s^H = \frac{1}{\sqrt{2}}\left[|B_s\rangle + |\bar{B}_s\rangle\right] \qquad CP \text{ odd}$$

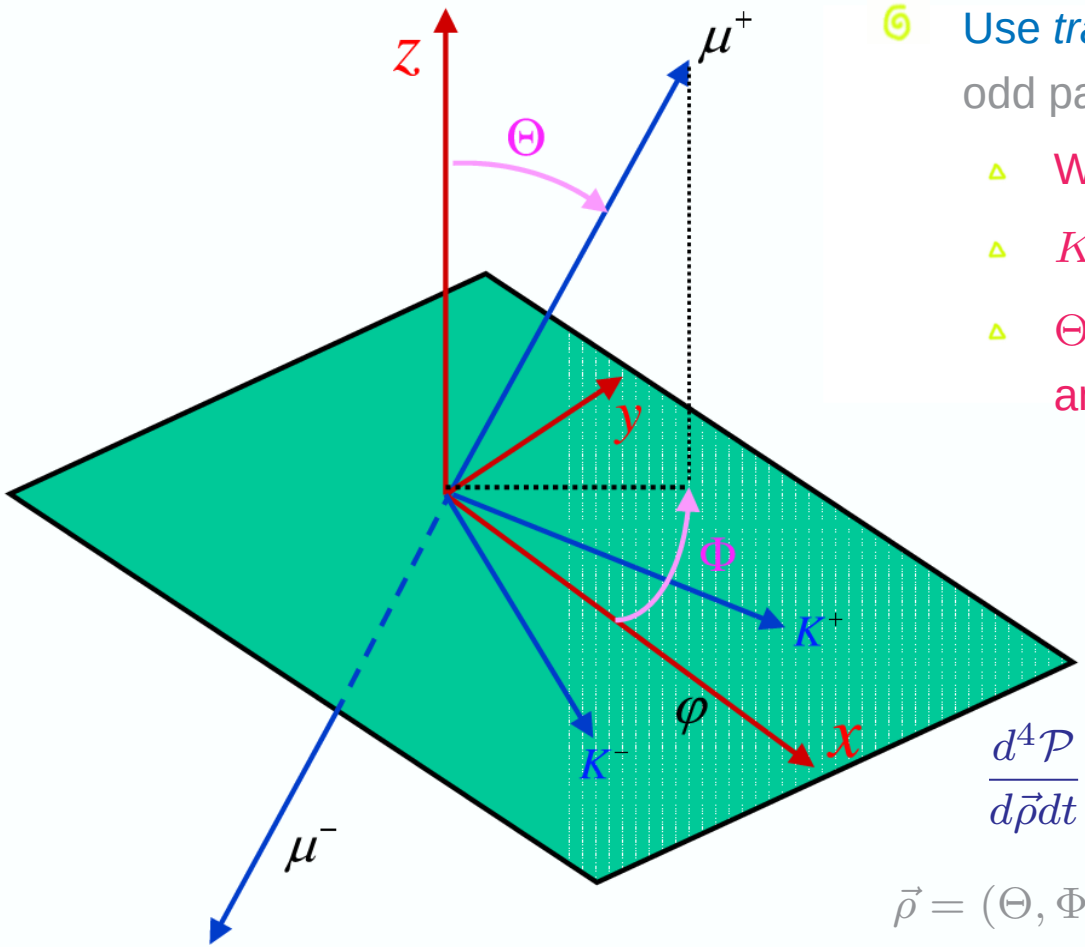
$$B_s^L = \frac{1}{\sqrt{2}}\left[|B_s\rangle - |\bar{B}_s\rangle\right] \qquad CP \text{ even}$$

  - Use $B_s \to J/\psi\phi$ w/final state $J = 0$ since J/ψ & ϕ have $S = 1$ this $\Rightarrow \ell = 0, 1, 2$ (S, P, D wave)
  - S & $D \Rightarrow CP$ even
  - $P \Rightarrow CP$ odd

- Goal is to disentangle different ℓ states

$\Delta\Gamma_s$ *Analysis*

Transversity Angles



- Use $B_s \to J/\psi\phi$
- Use *transversity* angles—Separates odd parity states nicely
  - Work in J/ψ rest frame
  - K^+K^- defines x-y plane
  - Θ, Φ are μ^+ polar, azimuthal angles, Ψ helicity angle of K^+

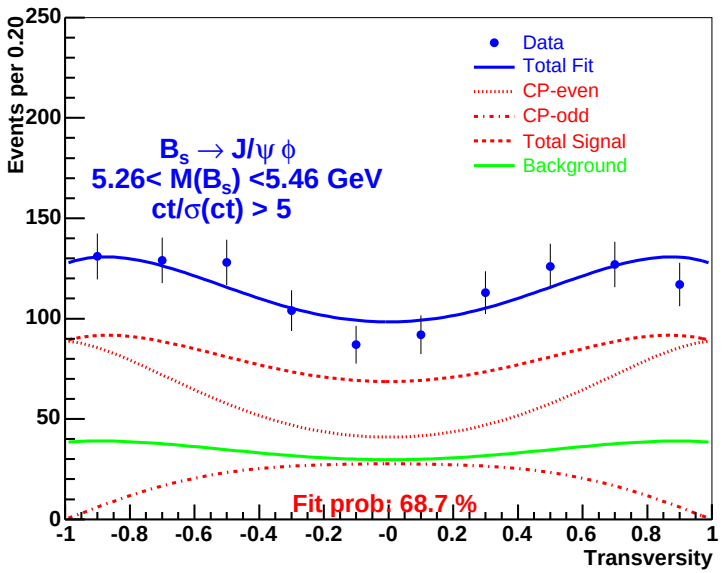
Angular Distribution B_s

$$\frac{d^4\mathcal{P}}{d\vec{\rho}dt} \propto f(\vec{\rho}, t; A_0, A_\perp, A_\parallel, \delta_1, \delta_2, \phi_s)$$

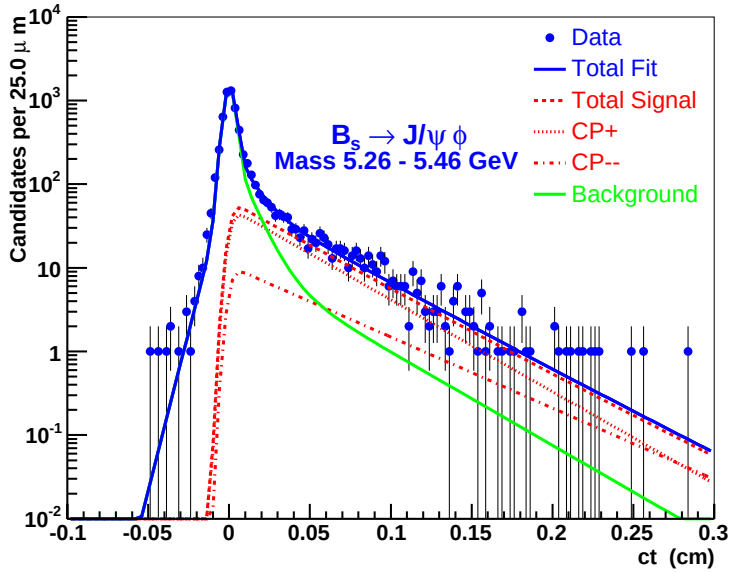
$$\vec{\rho} = (\Theta, \Phi, \Psi)$$

$\Delta\Gamma_s$ *Analysis*

Transversity Angle Θ



Lifetime



DØ Results

$\phi_s = -0.79 \pm 0.56 \pm 0.01$ Fit

$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.03$ ps^{-1}

$\bar{\tau} = 1.49 \pm 0.08^{+0.01}_{-0.03}$ ps

$\phi_s = 0$ Fixed

$\Delta\Gamma_s = 0.12 \pm 0.08^{+0.03}_{+0.04}$ ps^{-1}

$\bar{\tau} = 1.52 \pm 0.08^{+0.01}_{-0.04}$ ps

CP Asymmetry

- DØ measurement of mixing-induced CP asymmetry A_{SL} and phase ϕ_s —Flavor specific final states.
  - Measure untagged time-integrated muon asymmetry
  - Exclusive mode $B_s \to D_s^-(\phi\pi^-)\mu^+\nu X$

$$\frac{N(D_s\mu^+) - N(D_s\mu^-)}{N(D_s\mu^+) + N(D_s\mu^-)} = A_{SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

  - Inclusive mode $p\bar{p} \to \mu^\pm\mu^\pm$ (Like-sign asymmetry)

$$\frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = 2A_{SL}(\text{untagged})$$

- Both measurements use similar analysis methods

CP Asymmetry

- Systematics: Various detector & physics processes can cause an asymmetry.
  - Data split into 8 sample: split by sign of charge (q), rapidity (γ), toroid polarity (β)
  - Fit eight functions for 8 parameters

$$n_q^{\beta\gamma} = \frac{1}{4} N \epsilon^{\beta} (1 + qA)(1 + q\gamma A_{fb})(1 + \gamma A_{det}) \times (1 + q\beta\gamma A_{ro})(1 + q\beta A_{q\beta})(1 + \beta\gamma A_{\beta\gamma})$$

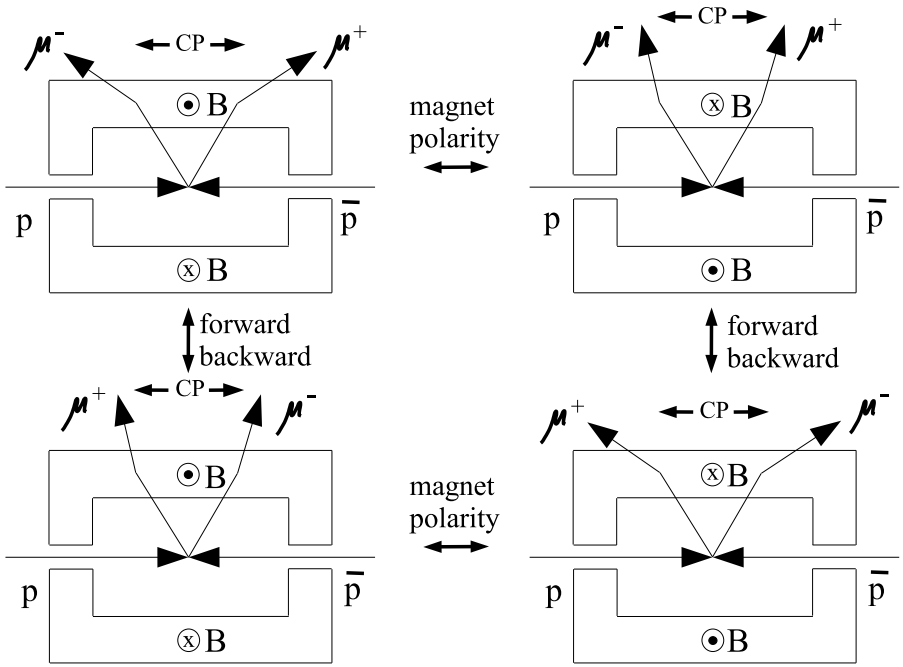
$n_q^{\beta\gamma}$: number of events in sample (given)

A: asymmetry from CP violation in B_s mixing

A_{xx}: detector and beam asymmetries

Detector Asymmetries—Examples

- Asymmetry w/toroid polarity β: $A^{\beta} = A + \beta A_{q\beta}$ (first order)
- Beam & detector asymmetries: $f(n_q^{\beta\gamma}) = A + A_{fb} A_{det}$ (second order)



A_{ro}: Change in detector acceptance and range out of muons in bending toward (away) from beamline

CP Asymmetry—Results

- Inclusive mode $p\bar{p} \to \mu^{\pm}\mu^{\pm}$ (Like-sign asymmetry)

$$\left.\begin{aligned} A &= -0.0005 \pm 0.0013 \\ \delta A &= -0.0023 \pm 0.0008 \end{aligned}\right\} \Rightarrow \quad A_{SL} = -0.0028 \pm 0.0013 \pm 0.0009$$

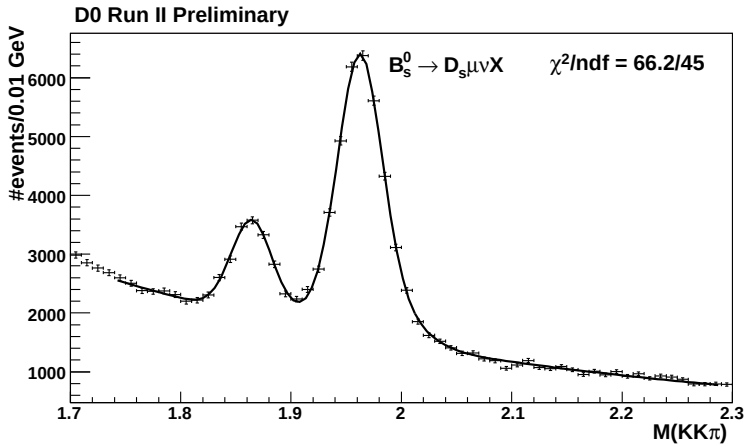
Combine with B-Factories to extract A^s_{SL}

δA asymmetry from $K^{\pm}$ decays: $K^+N \to$ hyperon, does not exist for K^-.

- Exclusive mode $B_s \to D_s^-(\phi\pi^-)\mu^+\nu X$

$$A^s_{SL} = 0.0245 \pm 0.0193 \pm 0.0035$$

Combine with $\Delta\Gamma_s$ and Δm_s to extract ϕ_s.



Direct CP Violation

- CDF measures $B_{(s)} \to hh'$ (recent result on $B_{(s)} \to K^-\pi^+$)
- Standard Model predicts for $B_{(s)} \to K^-\pi^+$

$$|A(B_s \to \pi^+K^-)|^2 - |A(\bar{B}_s \to \pi^-K^+)|^2$$
$$= |A(\bar{B}_d \to \pi^+K^-)|^2 - |A(B_d \to \pi^-K^+)|^2$$

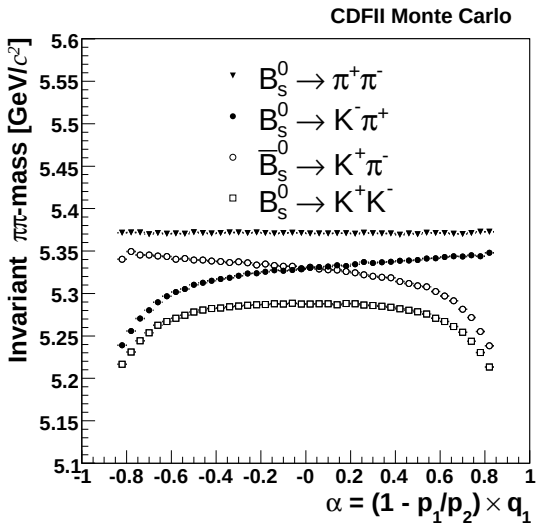
Direct CP violation in B_d measured by BaBar, Belle, CDF

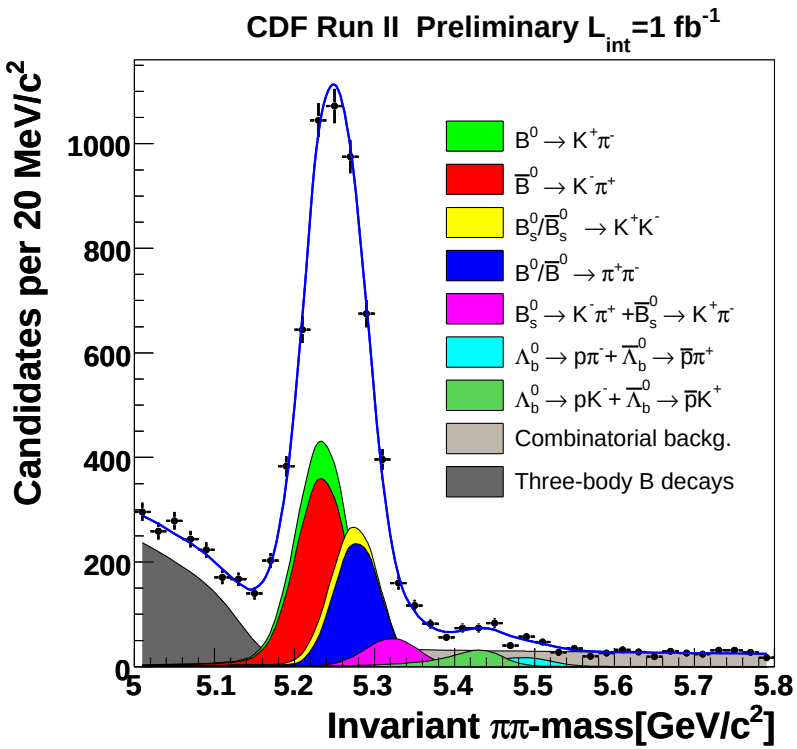
  - Direct CP violation requires amplitudes with different strong and weak phases (this mode dominated by penguin diagram)
  - Expected only in the SM (new physics would have hard time accommodating this result)

- Asymmetry can be used to measure CKM angle γ

Direct CP Violation

- Trigger on pair of opposite charge tracks with displaced vertex
- Impose isolation
- Assume tracks are pions
- Likelihood to separate modes (Includes particle ID, p_{tot}, M_{ij}, signed momentum imbalance (α))





Correction for difference in K^+ K^- interaction in material

Direct CP Violation

- First observation of $B_s \to \pi^+ K^-$ with significance of 8.2σ
- $A_{CP}(B_s \to \pi^+ K^-) = 0.39 \pm 0.15 \pm 0.08$
  - Comparison to B_d —consistent with SM

$$\frac{|A(\bar{B}_d \to \pi^+ K^-)|^2 - |A(B_d \to \pi^- K^+)|^2}{|A(B_s \to \pi^+ K^-)|^2 - |A(\bar{B}_s \to \pi^- K^+)|^2} = 0.84 \pm 0.42 \pm 0.15$$

B_d previously measured by BaBar, Belle, CDF

- Branching ratio $\mathcal{B}(B_s^0 \to K^- \pi^+) = (5.0 \pm 0.75 \pm 0.36) \times 10^{-6}$

SM Prediction: $\mathcal{B}(B_s^0 \to K^- \pi^+) = 4.9 \times 10^{-6}$
World average: $\mathcal{B}(B_d^0 \to K^+ \pi^-) = (19.7 \pm 0.6) \times 10^{-6}$

Summary

This talk has concentrated on B_s decays, but the Tevatron has produced a large number of other B-physics results.

- CDF measures B_s^0-$\bar{B}_s^0$
  - $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}
- DØ measures $\Delta\Gamma_s$ and ϕ_s
  - $\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.03$ ps^{-1} & $\phi_s = -0.79 \pm 0.56 \pm 0.01$
- DØ measures semileptonic decay asymmetry
  - Exclusive mode: $A_{SL}^s = 0.0245 \pm 0.0193 \pm 0.0035$
  - Inclusive mode: $A_{SL} = -0.0028 \pm 0.0013 \pm 0.0009$
- CDF measures direct CP violation in $B_s \to K^-\pi^+$
  - $A_{CP}(B_s \to \pi^+K^-) = 0.39 \pm 0.15 \pm 0.08$