Heavy flavour @ Tevatron
Status and prospects

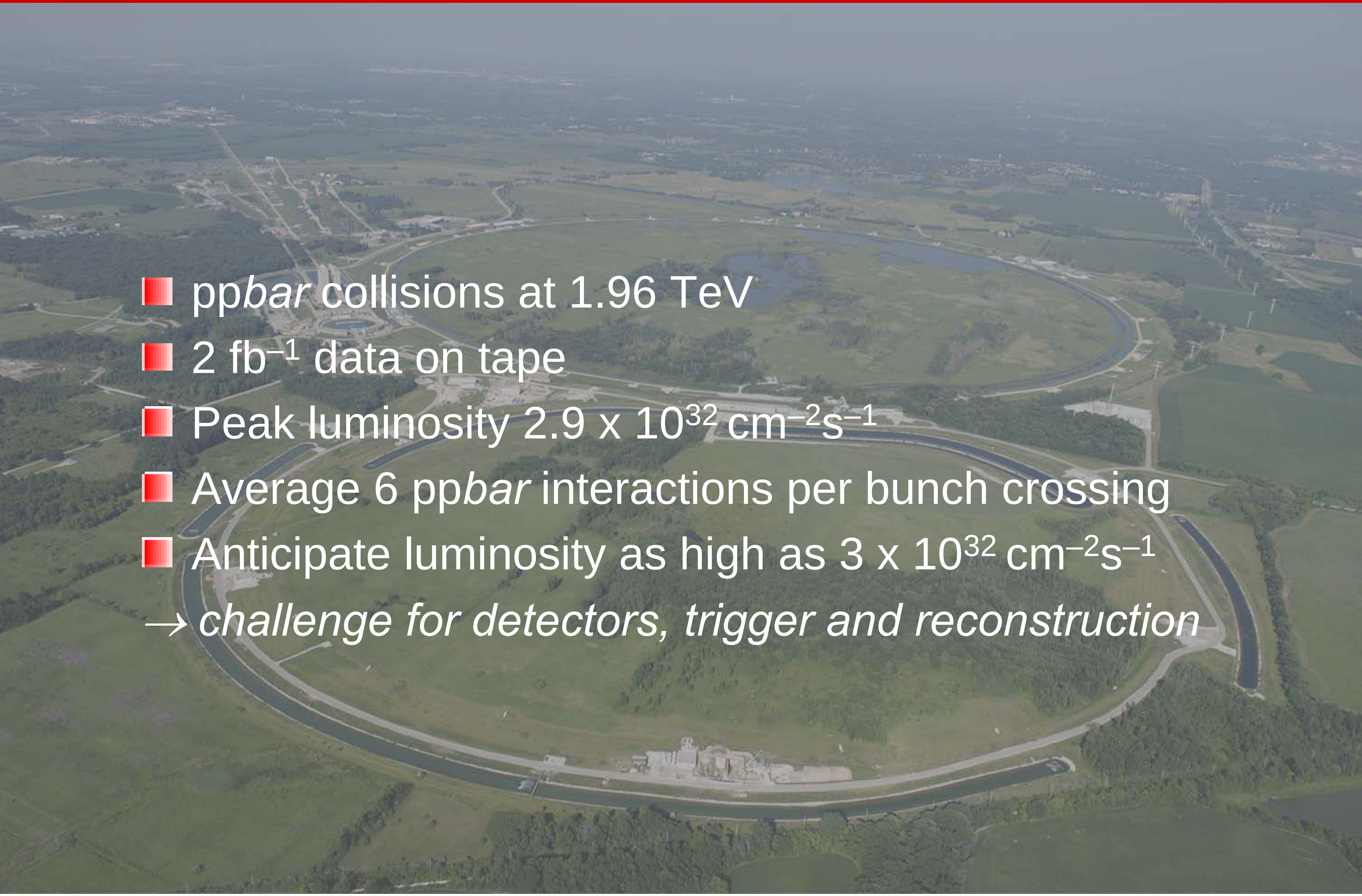
Flavour in the era of the LHC
March 2007

Jónatan Piedra
MIT

Outline

- The Tevatron Collider
- The D∅ and CDF II Detectors
- B_s Mixing
- $\Delta\Gamma_s$ and ϕ_s
- $B \to hh'$
- $B \to \mu\mu$
- $\Lambda_b \to J/\psi\ \Lambda$ Lifetime
- Observation of Σ_b
- Prospects

The Tevatron Collider



- pp*bar* collisions at 1.96 TeV
- 2 fb^{-1} data on tape
- Peak luminosity $2.9 \times 10^{32}\ cm^{-2}s^{-1}$
- Average 6 pp*bar* interactions per bunch crossing
- Anticipate luminosity as high as $3 \times 10^{32}\ cm^{-2}s^{-1}$

$\rightarrow$ *challenge for detectors, trigger and reconstruction*

The DØ and CDF II Detectors

- CDF II
  - strong central tracking
  - silicon vertex detector and trigger
  - particle ID (TOF and dE/dx)
  - excellent mass resolution
- DØ
  - excellent coverage of tracking and muon systems
  - excellent calorimetry and electron ID
  - 2 T solenoid, polarity reversed weekly
  - April 2006 Layer 0 installation

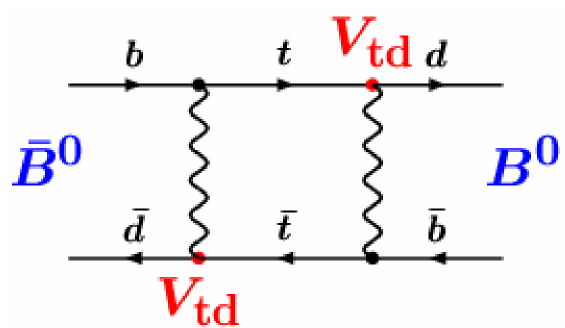
Neutral *B* Meson Oscillations

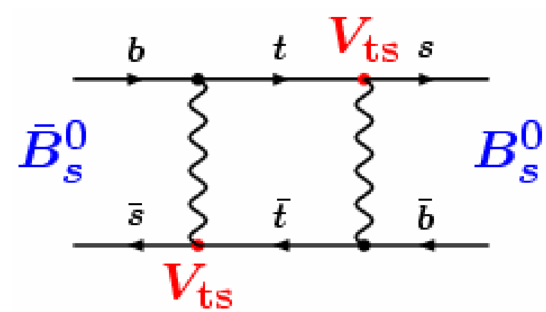
- The eigenstates of the weak interaction are different from those of the strong interaction ⇒ mixing in quark families

WEAK (FLAVOR) EIGENSTATES

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

STRONG (MASS) EIGENSTATES





- Oscillation frequencies Δm_d and Δm_s determine poorly known V_{td} and V_{ts}
- Theoretical uncertainties reduced in ratio, *11% → 3%*

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}, \qquad \xi = 1.210^{+0.047}_{-0.035}$$

Lattice QCD, hep/lat-0510113

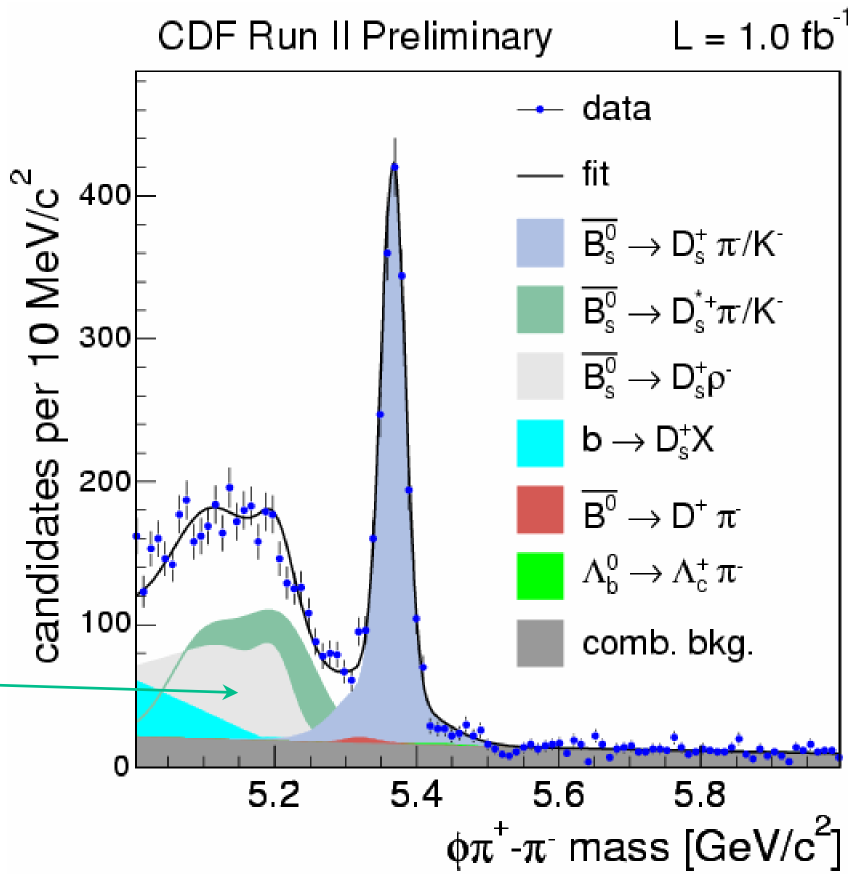
B_s *Mixing* Signal

- Cleanest topology

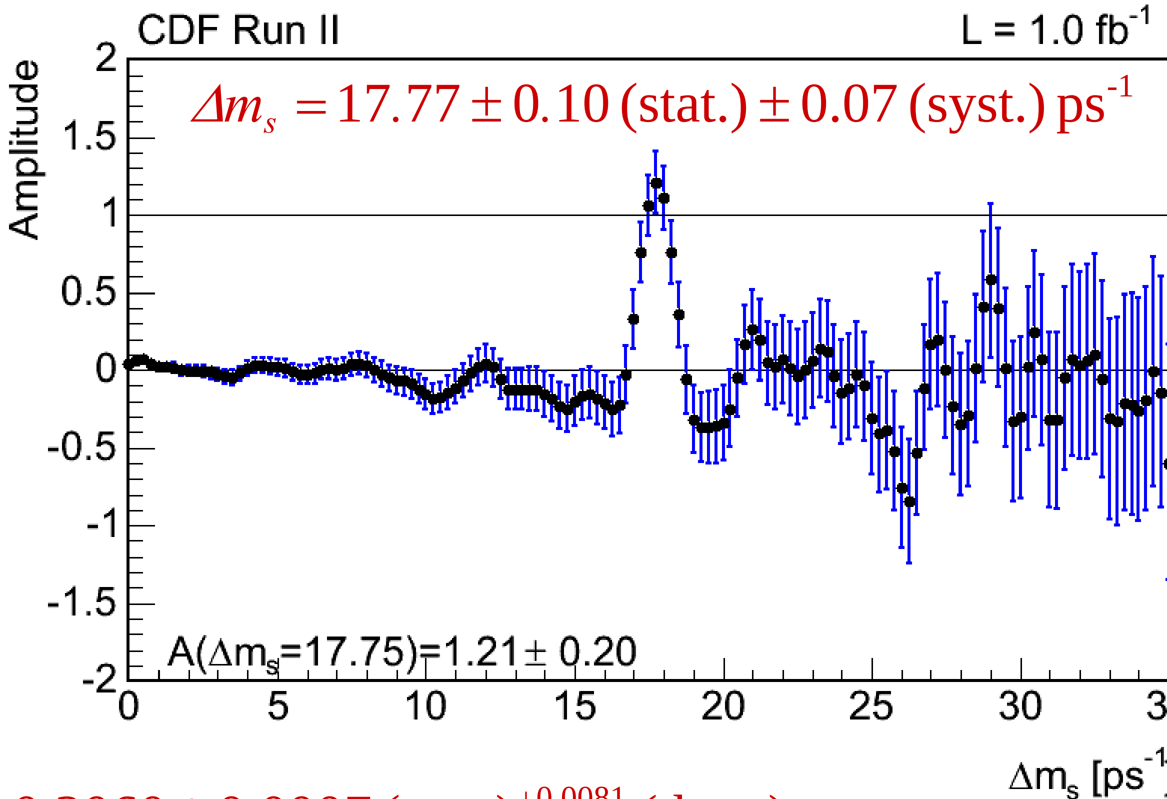
$$B_s^0 \to D_s^- \pi^+$$
$$D_s^- \to \phi \pi^-$$
$$\left(D_s^- \to \overline{K}^{*0} K^-, \pi^- \pi^+ \pi^-\right)$$

- Includes partially reconstructed decays

$$D_s^{*-} \pi^+, D_s^- \rho^+$$



- Total signal
  - 8,800 fully reconstructed decays
  - 61,500 semileptonic decays



Phys. Rev. Lett. 97, 242003 (2006)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\text{exp.})^{+0.0081}_{-0.0060}\,(\text{theo.})$$

- Probability that a random fluctuation mimics signal = 8 x $10^{-8} \Rightarrow 5.4\sigma$

1.2 fb^{-1}

Double-sided 90% CL, 17 < Δm_s < 21 ps^{-1}

Phys. Rev. Lett. 97, 061802 (2006)

$\Delta\Gamma_s$ and ϕ_s Motivation

- *L*ight and *H*eavy B_s mass eigenstates

$$\Delta m_s \equiv M_H - M_L$$
$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$$

- The mass eigenstates are expected to be almost pure CP eigenstates
- The CP violating mixing phase is predicted to be

$$\phi_s = (4.2 \pm 1.4) \times 10^{-2}$$

A.Lenz & U.Nierste, hep-ph/0612167

- New Physics may alter ϕ_s leading to a reduction of the observed $\Delta\Gamma_s$

$$\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos \phi_s|$$

$\Delta\Gamma_s$ and ϕ_s $B_s \to J/\psi\, \phi$

- *1.1 fb^{-1}*
- $B_s \to J/\psi\, \phi$
  - $J/\psi \to \mu^+\mu^-$
  - $\phi \to K^+K^-$

260 pb^{-1}

$$\Delta\Gamma = 0.47^{+0.19}_{-0.24}\,(\text{stat.}) \pm 0.01\,(\text{syst.})\,\text{ps}^{-1}$$

CDF update coming soon

- Fit time dependent angular distributions, mass and lifetime
  - direct constraint on ϕ_s
  - 4-fold ambiguity, $\pm\phi_s$ and $\pm(\pi - \phi_s)$

the sign of sinϕ_s is reversed with the simultaneous reversal of the signs of the cosines of the CP-conserving strong phases δ_1 and δ_2

$$|\phi_s| = 0.79 \pm 0.56\,(\text{stat.})^{+0.01}_{-0.14}\,(\text{syst.})$$

$$\Delta\Gamma_s = 0.17 \pm 0.08\,(\text{stat.}) \pm 0.02\,(\text{syst.})\,\text{ps}^{-1}$$

$$|\phi_s| = 2.35 \pm 0.56\,(\text{stat.})^{+0.14}_{-0.01}\,(\text{syst.})$$

$$\Delta\Gamma_s = -0.17 \pm 0.08\,(\text{stat.}) \pm 0.02\,(\text{syst.})\,\text{ps}^{-1}$$

consistent with the SM prediction

Flavor Specific Decays

- Flavor specific decays of B_s provide independent constraints
- An effective mean lifetime $\tau_{fs} = 1/\Gamma_{fs}$ is related to the physical parameters

  hep-ph/0201071, p.360

$$\Gamma_{fs} = \overline{\Gamma}_s - \frac{(\Delta\Gamma_s)^2}{2\overline{\Gamma}_s} + \frac{O(\Delta\Gamma_s)^3}{\overline{\Gamma}_s^{\,2}}$$

- Use world average value $\tau_{fs} = 1.440 \pm 0.036$ ps
  - includes recent D∅ measurement

$$\tau_{fs} = 1.398 \pm 0.044\,(\text{stat.})^{+0.028}_{-0.025}\,(\text{syst.})\text{ ps}$$

Charge Asymmetry

- Another constraint on the parameters of the B_s system
- Measurement of the semileptonic charge asymmetry induced by B_s mixing
- Measurement "*a*"

$$A_{SL}^{\mu\mu} = \frac{N\left(b\bar{b} \to \mu^+\mu^+X\right) - N\left(b\bar{b} \to \mu^-\mu^-X\right)}{N\left(b\bar{b} \to \mu^+\mu^+X\right) + N\left(b\bar{b} \to \mu^-\mu^-X\right)}$$

$$a_{SL}^{s} = -0.0064 \pm 0.0101$$

input from *B*-factories

$$\frac{1}{2}a_{SL}^{s} = A_{SL}^{s,untagged} \equiv \frac{N\left(\bar{B}_s \to \ell^+X\right) - N\left(B_s \to \ell^-X\right)}{N\left(\bar{B}_s \to \ell^+X\right) + N\left(B_s \to \ell^-X\right)}$$

$$a_{SL}^{s} = \frac{x_s^2 + y_s^2}{1 + x_s^2}\frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s \cong \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

$$x_s \equiv \frac{\Delta m_s}{\bar{\Gamma}_s}, \quad y_s \equiv \frac{\Delta\Gamma_s}{2\bar{\Gamma}_s}$$

- Measurement "*b*"

$$A_{SL}^{s,untagged} = \frac{N\left(\mu^+D_s^-\right) - N\left(\mu^-D_s^+\right)}{N\left(\mu^+D_s^-\right) - N\left(\mu^-D_s^+\right)} \Rightarrow a_{SL}^{s} = +0.0245 \pm 0.0193\,(\text{stat.}) \pm 0.0035\,(\text{syst.})$$

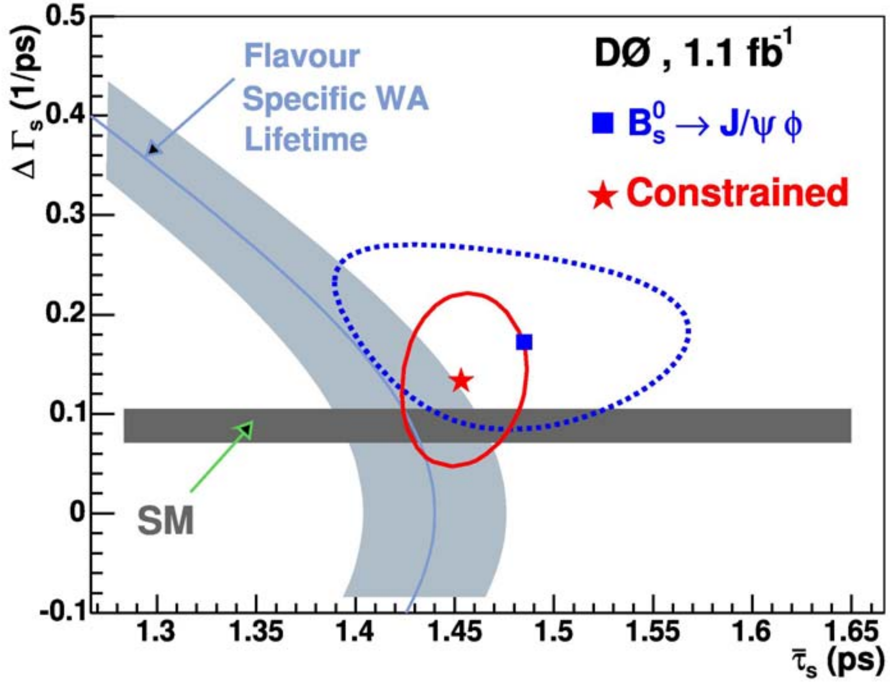
- "*a*" and "*b*" are nearly independent (correlation < 1%)
- Combination → best estimate of charge asymmetry in semileptonic B_s

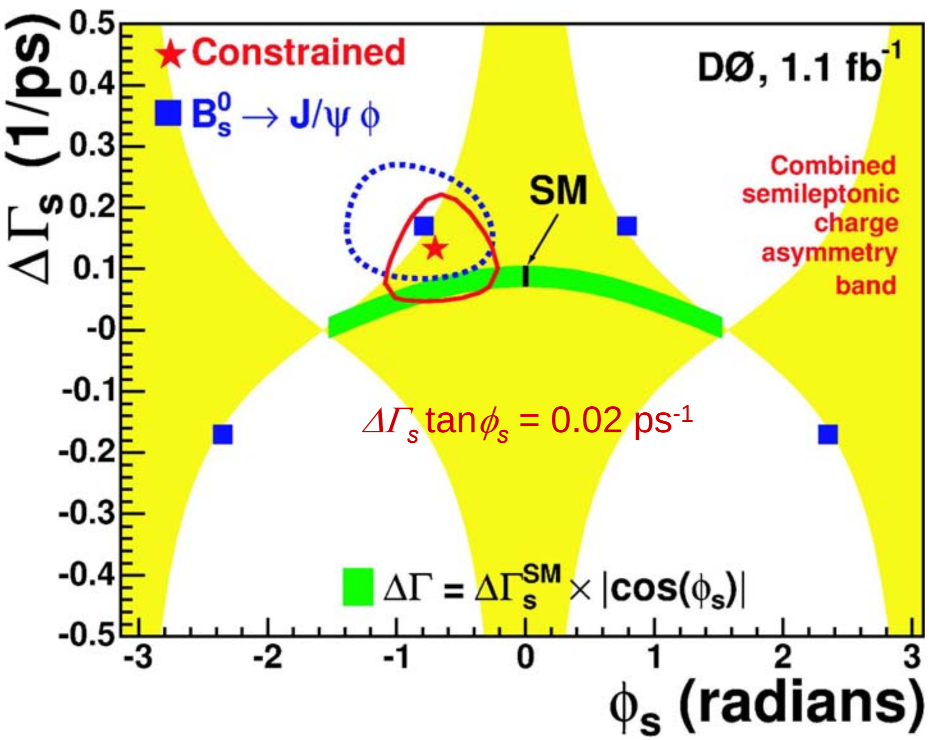
$$a_{SL}^{s} = 0.0001 \pm 0.0090$$

$$\Delta\Gamma_s \tan\phi_s = 0.02 \pm 0.16\ \text{ps}^{-1}$$

$\Delta\Gamma_s$ and ϕ_s Results

- Repeat fit to $B_s \rightarrow J/\psi\,\phi$ (1 fb^{-1}) with
  - constraint from charge asymmetry
  - constraint from WA τ_{fs}
- The contours indicate error ellipses $\Delta ln(\mathcal{L}) = 0.5$ (39% CL)





- ϕ_s ambiguity remains unsolved
- For the solution with

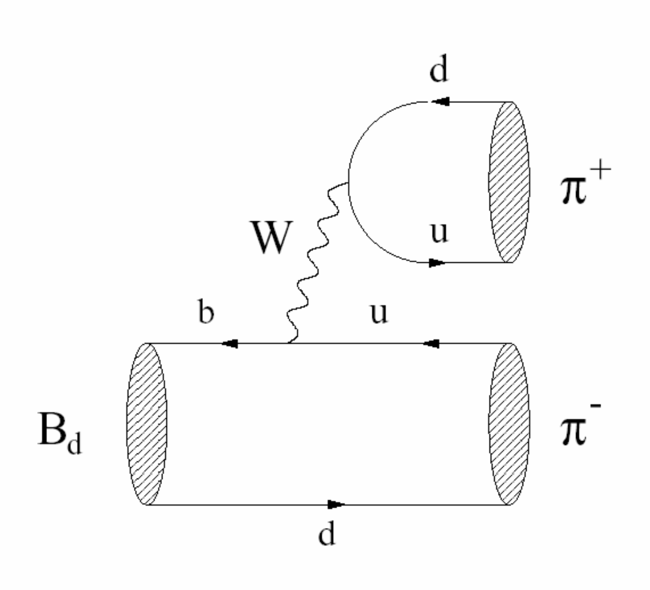
  $\phi_s < 0$, $\cos\,\delta_1 > 0$ and $\cos\,\delta_2 < 0$

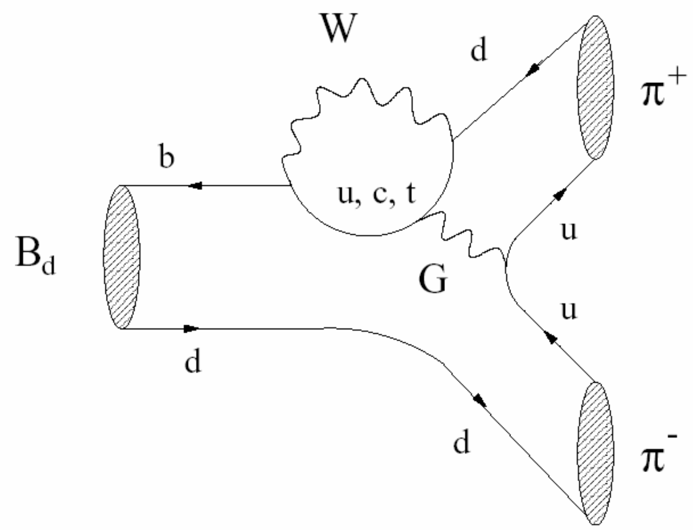
$$\Delta\Gamma_s = 0.13 \pm 0.09\ \mathrm{ps}^{-1}$$

$$\phi_s = -0.70^{+0.47}_{-0.39}$$

$B \to hh'$ Motivation

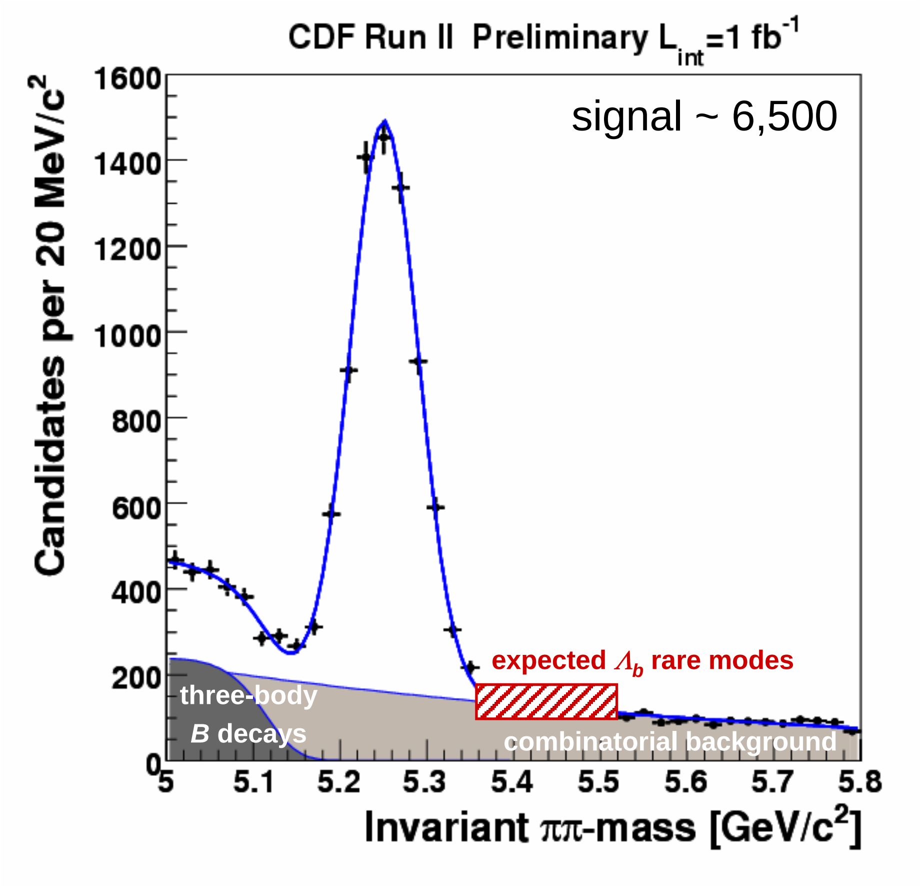
- The Tevatron has access to B_s, B^0 and baryons
  - physics program complementary to the e^+e^- B-factories
- Currently accesible BR can constrain theory
  - compare measurements with allowed regions in spaces of $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ observables
  - probe for New Physics





$B \to hh'$ Strategy

- Two sets of optimized cuts
  - (loose) to measure $A_{CP}(B^0 \to K^+\pi^-)$
  - (tight) to observe $B_s \to K^-\pi^+$ and measure $N(B_s \to K^-\pi^+) / N(B^0 \to K^+\pi^-)$



- Despite excellent mass resolution (23 MeV/c) modes overlap in a peak
- PID resolution is insufficient for event-by-event separation
- Fit signal composition with a likelihood that combines information from kinematics (mass and momenta) and particle ID (dE/dx)

$B \to hh'$ BR Results

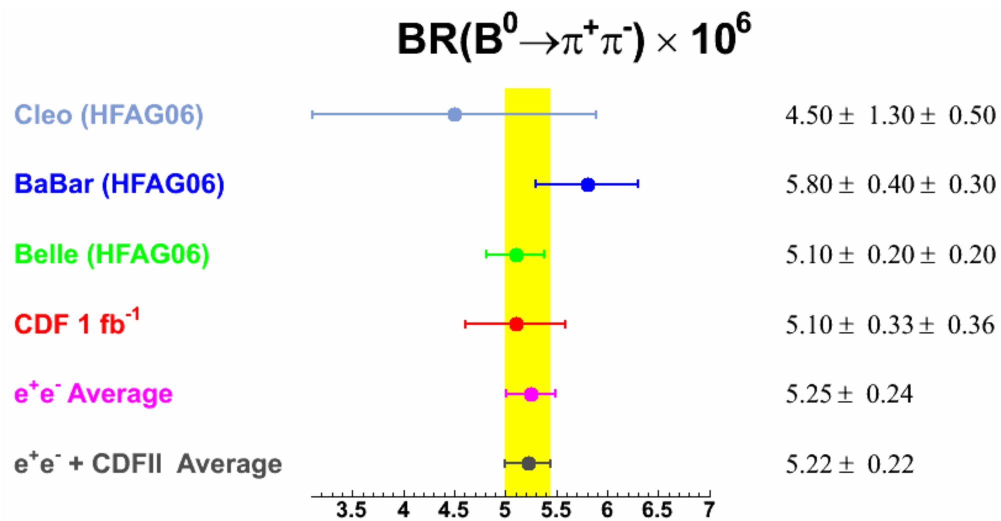
- Measured

$$\frac{BR\left(B^0 \to \pi^+\pi^-\right)}{BR\left(B^0 \to K^+\pi^-\right)} = 0.259 \pm 0.017\,(\text{stat.}) \pm 0.016\,(\text{syst.})$$

- Using HFAG 2006 averaged values

$$BR\left(B^0 \to \pi^+\pi^-\right) = \left(5.10 \pm 0.33\,(\text{stat.}) \pm 0.36\,(\text{syst.})\right) \times 10^{-6}$$

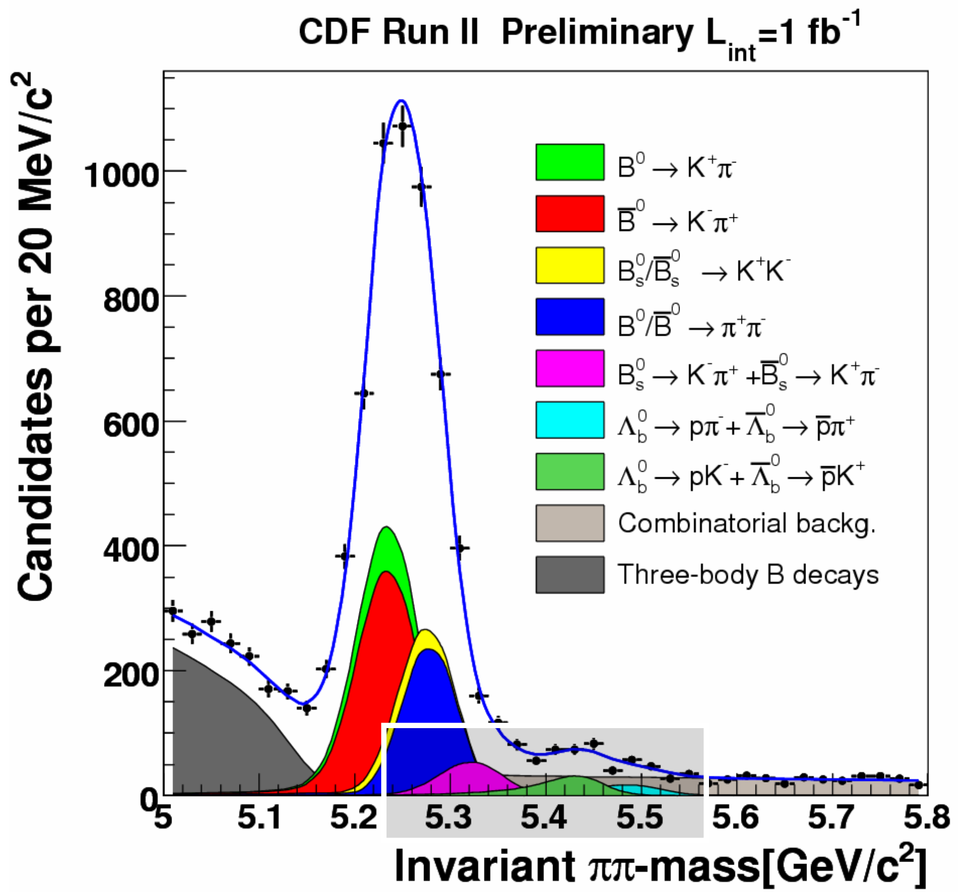
$$BR\left(B_s \to K^+K^-\right) = \left(24.4 \pm 1.4\,(\text{stat.}) \pm 4.6\,(\text{syst.})\right) \times 10^{-6}$$



- *$BR(B^0 \to \pi^+\pi^-)$* in agreement with *B*-factories measurement

$B \to hh'$ Rare Modes

- Signal = 6 modes combination
  - $B^0 \to \pi^+\pi^- / K^+\pi^-$ and $B_s \to K^+K^-$ already established
- Set limits on annihilation modes
  - $B_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$
- 3 new rare modes observed



$$N_{raw}\left(B_s^0 \to K^-\pi^+\right) = 230 \pm 34\,(\text{stat.}) \pm 16\,(\text{syst.}) \quad 8\sigma$$

$$N_{raw}\left(\Lambda_b^0 \to pK^-\right) = 156 \pm 20\,(\text{stat.}) \pm 11\,(\text{syst.}) \quad 11\sigma$$

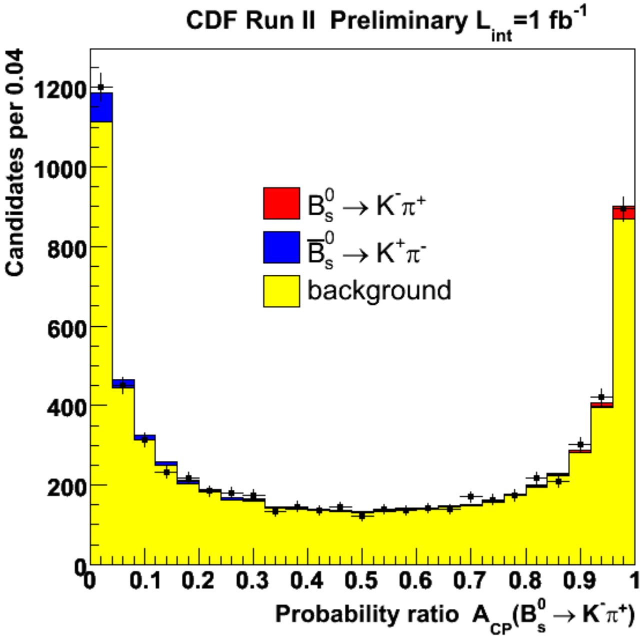
$$N_{raw}\left(\Lambda_b^0 \to p\pi^-\right) = 110 \pm 18\,(\text{stat.}) \pm 16\,(\text{syst.}) \quad 6\sigma$$

$B \to hh'$ Direct CP Asymmetry

- "Is observed direct CP violation in $B^0 \to K^+\pi^-$ due to NP?
  Check SM prediction of equal violation in $B_s \to K^-\pi^+$"

Lipkin, Phys. Lett. B621:126 (2005)
Gronau & Rosner Phys.Rev. D71 074019 (2005)

- Expect large $A_{CP}(B_s \to K^-\pi^+) \approx 0.37$
- Sign opposite to $A_{CP}(B^0 \to K^+\pi^-)$



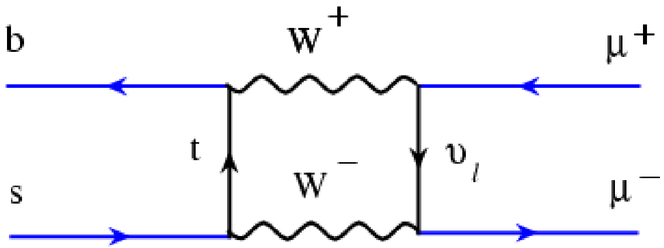
$$A_{CP} = \frac{N\left(\overline{B}^0 \to K^-\pi^+\right) - N\left(B^0 \to K^+\pi^-\right)}{N\left(\overline{B}^0 \to K^-\pi^+\right) + N\left(B^0 \to K^+\pi^-\right)} = -0.086 \pm 0.023\,(\text{stat.}) \pm 0.009\,(\text{syst.})$$

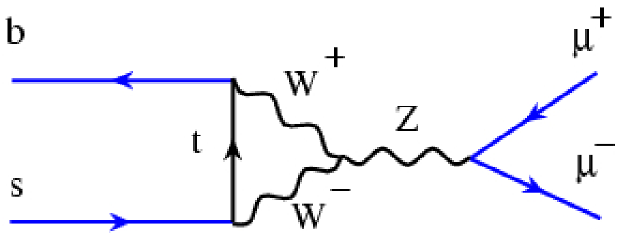
$$A_{CP} = \frac{N\left(\overline{B}_s \to K^+\pi^-\right) - N\left(B_s \to K^-\pi^+\right)}{N\left(\overline{B}_s \to K^+\pi^-\right) + N\left(B_s \to K^-\pi^+\right)} = +0.39 \pm 0.15\,(\text{stat.}) \pm 0.08\,(\text{syst.})$$

First measurement of CP asymmetry in the B_s system

$B \to \mu\mu$ Motivation and Strategy

- Standard Model prediction very suppressed





$$BR(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

- Sizeable New Physics enhancement predicted in many scenarios

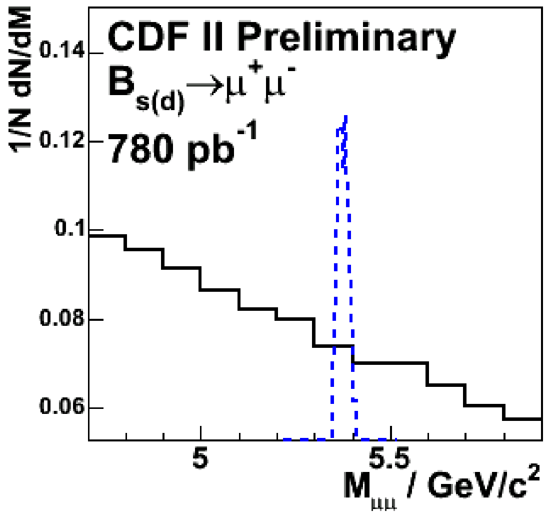
- Blind optimization using signal Monte Carlo and sideband data
- Normalize to known $B^+ \to J/\psi K^+$

$$BR(B_s \to \mu^+\mu^-) = \frac{N_{B_s}}{N_{B^+}} \frac{\alpha_{B^+} \cdot \varepsilon_{B^+}^{total}}{\alpha_{B_s} \cdot \varepsilon_{B_s}^{total}} \frac{f_{b \to B^+}}{f_{b \to B_s}} BR(B^+ \to J/\psi K^+) BR(J/\psi \to \mu^+\mu^-)$$

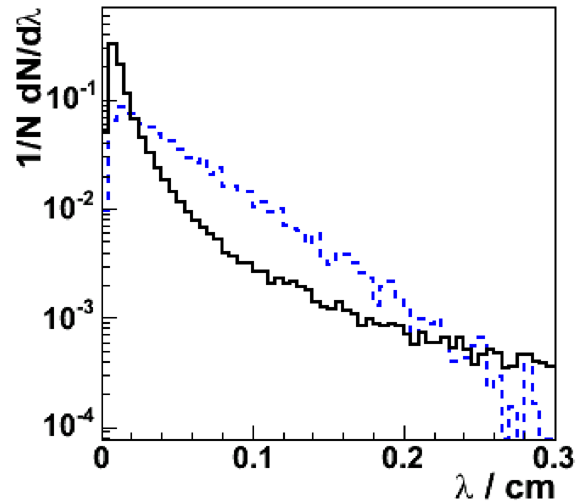
- Reconstruct normalization mode in the same data, applying same criteria
- Evaluate expected background, open the box and calculate *BR* or limit

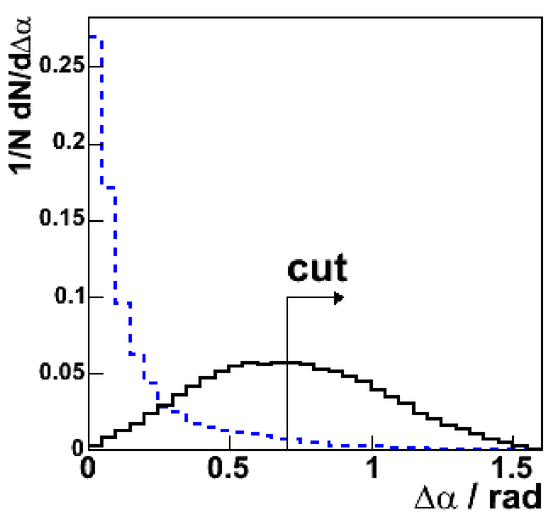
$B \to \mu\mu$ Signal Discrimination

$M_B \pm 2.5\sigma$ (~120 MeV) mass window

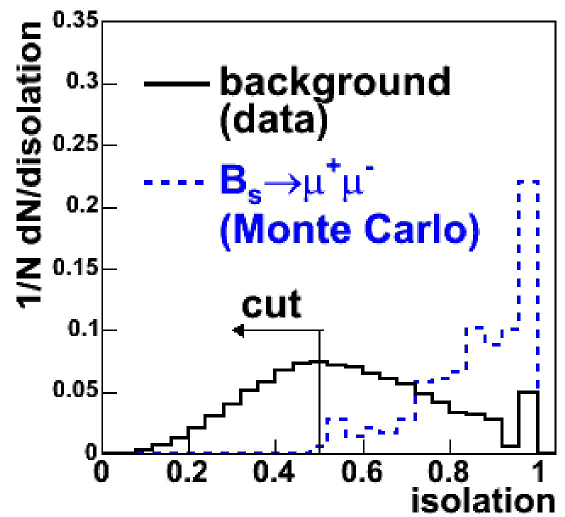


vertex displacement $\lambda = L M_B / p_B$





angle between p_B and decay axis



fraction of $p_T(B)$ within $\Delta R = 1$

$B \to \mu\mu$ Results

- 780 pb^{-1} CDF B_s limit
  - BR($B_s \to \mu\mu$) < 8 (10) x 10^{-8} @ 90% (95%) C.L.

CDF update coming soon (sensitivity x2)

- 2 fb^{-1} DØ B_s limit
  - BR($B_s \to \mu\mu$) < 7.5 (9.3) x 10^{-8} @ 90% (95%) C.L.

- 780 pb^{-1} CDF B^0 limit, world's best
  - BR($B^0 \to \mu\mu$) < 2.3 (3.0) x 10^{-8} @ 90% (95%) C.L.

$$\frac{BR(B^0)\,\mathrm{limit}}{BR(B^0)\,\mathrm{SM}} \approx 300 \qquad \frac{BR(B_s)\,\mathrm{limit}}{BR(B_s)\,\mathrm{SM}} \approx 20$$

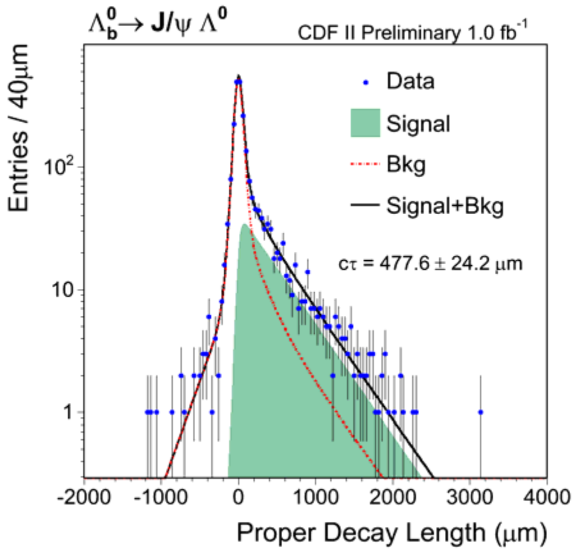
110 fb^{-1} BaBar *hep-ex/0408096*

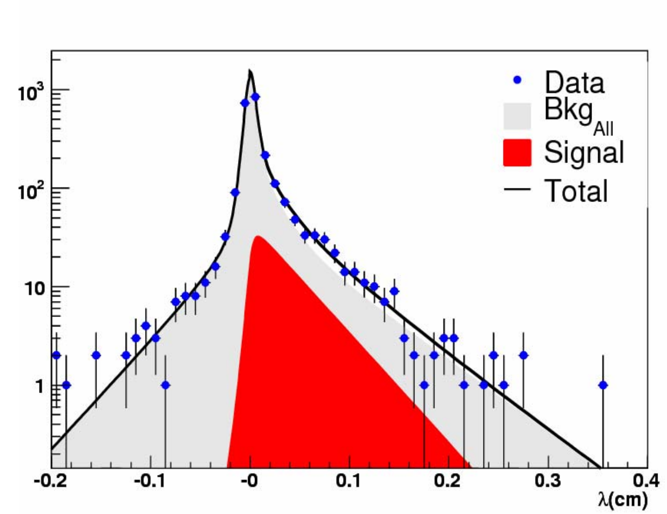
BR($B^0 \to \mu\mu$) < 8.3 x 10^{-8} @ 90% C.L.

$\Lambda_b \to J/\psi\ \Lambda$ Lifetime Results

- CDF and DØ have measured $\Lambda_b \to J/\psi\ \Lambda$ lifetime
- Smaller boost uncertainty than $\Lambda_b \to \Lambda_c\ l\nu$ *(world average dominated)*
- Earlier $\tau(\Lambda_b)/\tau(B^0)$ ~ 0.94 predictions were 2σ above experiment
  - new calculations including higher order effects predict lower ratio

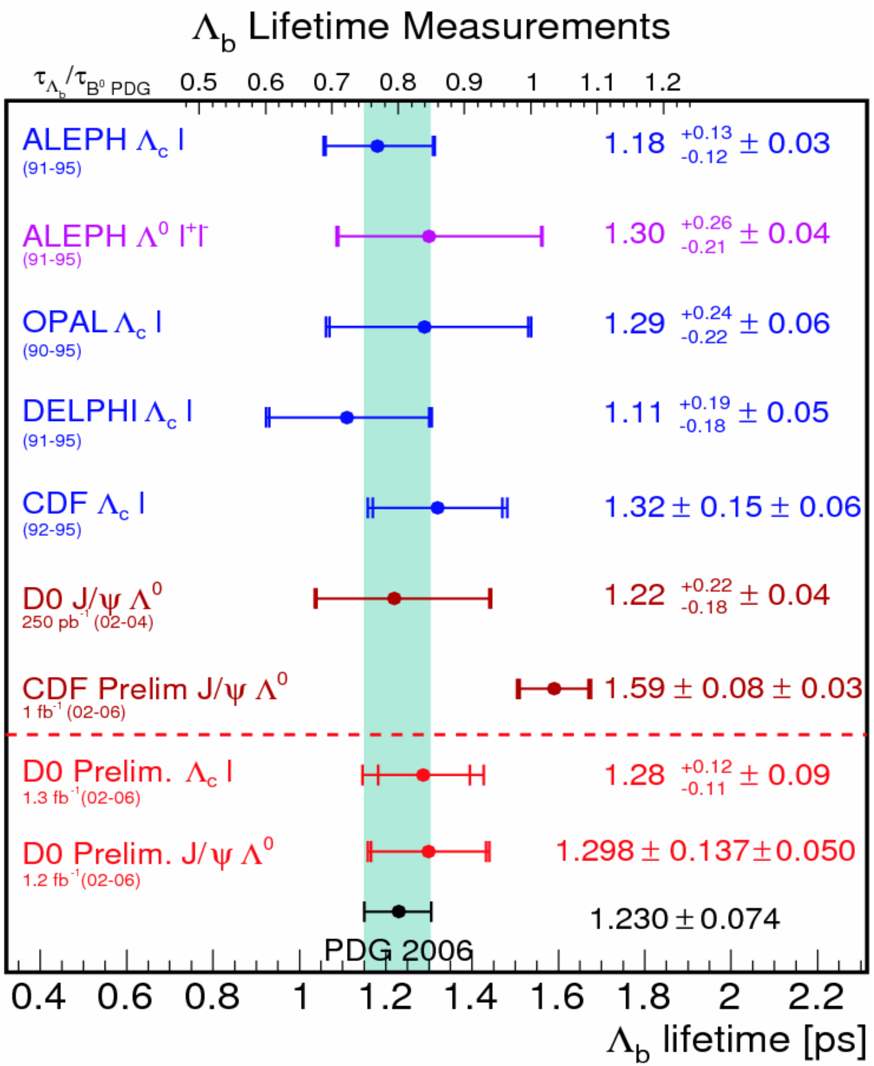
	CDF 1.0 fb^{-1}	DØ 1.2 fb^{-1}
signal	538 ± 38	174 ± 21
$\tau(\Lambda_b)$ [ps]	$1.593^{+0.083}_{-0.078}$ (stat.) ± 0.033 (syst.)	1.298 ± 0.137 (stat.) ± 0.050 (syst.)





Summary

- Current NLO QCD + $1/m_b^4$
  $\tau(\Lambda_b)/\tau(B^0) = 0.86 \pm 0.05$
- HFAG 2005 world average
  $\tau(\Lambda_b)/\tau(B^0) = 0.803 \pm 0.047$
- New CDF result
  about 3σ above PDG 2006
- New D∅ results
  consistent with PDG 2006 & CDF
- Need more experimental inputs
- Soon $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ lifetime from CDF
  yield ~ 3,000



Observation of Σ_b

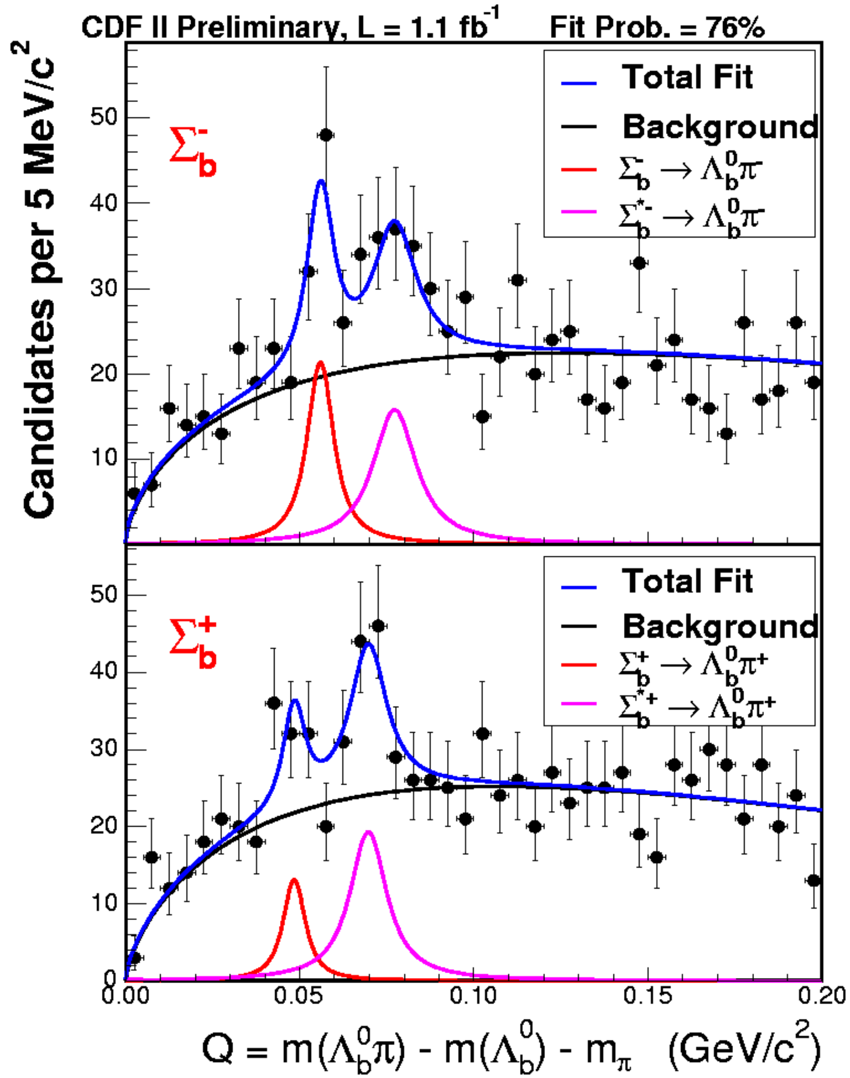
- Λ_b (*udb*) only established *b*-baryon
- Next accessible baryons:
  uub and *ddb* states
- Look at $\Lambda_b \rightarrow \Lambda_c \pi$ sample
- Signals consistent with lowest lying charged Σ_b states

$$\Sigma_b^{(*)+} \rightarrow \Lambda_b^0 \pi^+$$

$$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$$

$$\Lambda_c^+ \rightarrow p K^- \pi^+$$

Σ_b^+	$5808^{+2.0}_{-2.3}$ (stat.) ± 1.7 (syst.) MeV/c^2
Σ_b^-	$5816^{+1.0}_{-1.0}$ (stat.) ± 1.7 (syst.) MeV/c^2
Σ_b^{*+}	$5829^{+1.6}_{-1.8}$ (stat.) ± 1.7 (syst.) MeV/c^2
Σ_b^{*-}	$5837^{+2.1}_{-1.9}$ (stat.) ± 1.7 (syst.) MeV/c^2



Summary

- Very fast turn around of results at the Tevatron
  - DØ already showing 2 fb^{-1} results
- Competitive and complementary program to *B*-factories
- B_s mixing measured
  - Δm_s = 17.77 ± 0.10 (stat.) ± 0.07 (syst.) ps^{-1}
- First observation of
  - $B_s \to K^- \pi^+$
  - $\Lambda_b \to pK^-$
  - $\Lambda_b \to p\pi^-$
- First measurement of direct CPV in B_s
- $B \to \mu\mu$ limits ~10^{-8}
- Observation of Σ_b

Prospects I

- B_s mixing phase ϕ_s not constrained by Δm_s
- $\Delta\Gamma_s$ and ϕ_s from
  - $B_s \to J/\psi\, \phi$
  - $B_s \to K^+K^-$

360 pb^{-1}

$$\tau\left(B_s^0 \to K^+K^-\right) = 1.53 \pm 0.18\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$

$$\frac{\Delta\Gamma_s^{CP}\left(B_s^0 \to K^+K^-\right)}{\Gamma_s^{CP}\left(B_s^0 \to K^+K^-\right)} = -0.08 \pm 0.23\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

  - flavor specific decays $B_s \to D_s l\nu,\ D_s\pi$
  - semileptonic charge asymmetry A_{SL}
  - BR($B_s \to D_s^{(*)}\, D_s^{(*)}$)

1.3 fb^{-1}, submitted to PRL

$$BR\left(B_s^0 \to D_s^{(*)} D_s^{(*)}\right) = 0.039^{+0.019}_{-0.017}\,(\text{stat.})^{+0.016}_{-0.015}\,(\text{syst.})$$

$$\Delta\Gamma_s^{CP}/\Gamma_s = 0.079^{+0.038}_{-0.035}\,(\text{stat.})^{+0.031}_{-0.030}\,(\text{syst.})$$

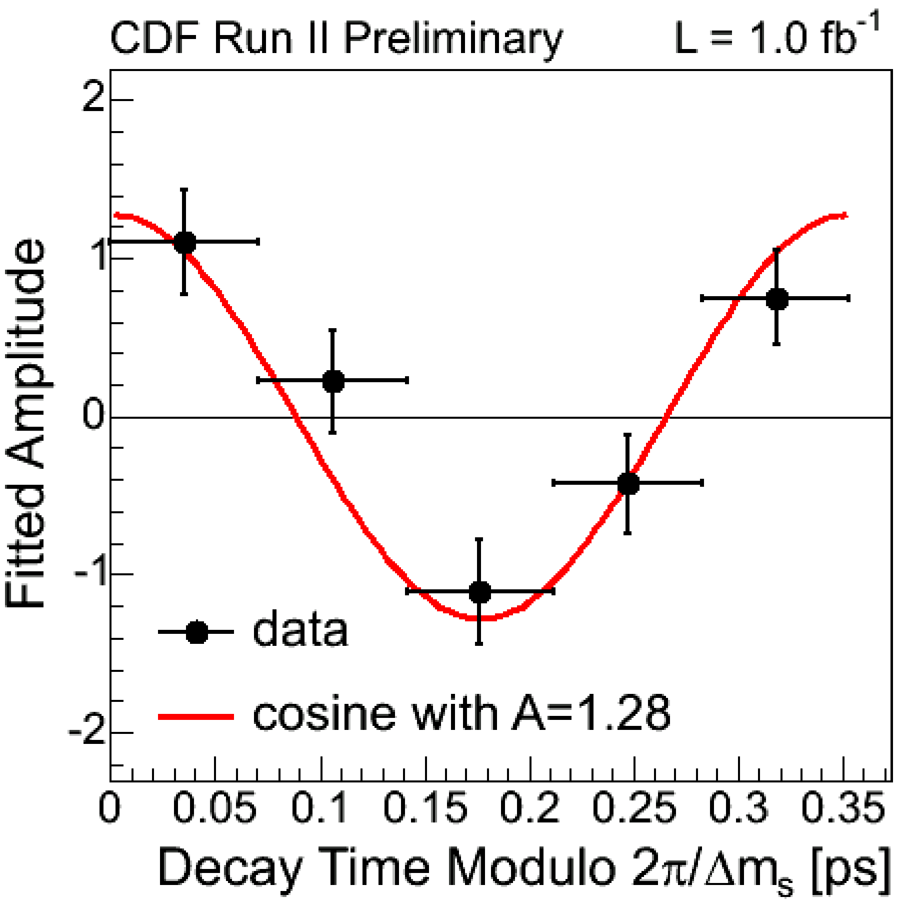
ALL THESE MEASUREMENTS SHOULD CONVERGE

Prospects II

- Direct measurement of ϕ_s
  - measure time dependent CP asymmetry in $B_s \to J/\psi\ \phi$
- A_{CP}^{mix} from $B_s \to J/\psi\ \phi$ ($A_{CP}^{mix,\ theory} = 0.07 \pm 0.50$)
- CKM angle $\gamma \sim 51^o \pm 20^o$
- D^0 mixing (evidence from Belle and BaBar)
- D^0 direct CP asymmetry
- Rare charm decays
  - $D^0 \to l^+ l'^-$ could be world's best
  - $D^+_{(s)} \to \pi\mu\mu$ or $K\mu\mu$
- New *b*-baryon decay modes
  - CDF looking at $\Xi_b^- \to \Xi_c^0 \pi^-, \Xi_b^- \to \Xi^- J/\psi$

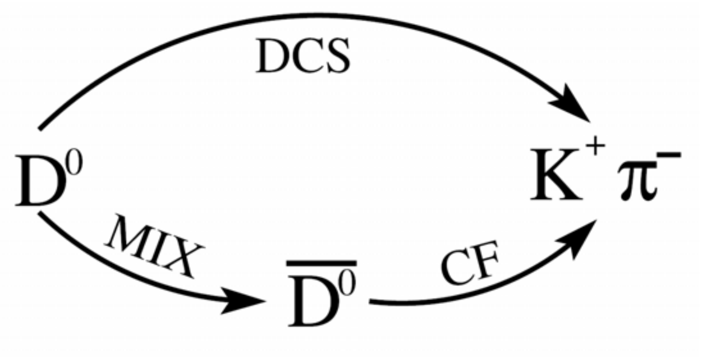
Backup

B_s *Mixing* Asymmetry



Charm Mixing

- Mixing observed in K^0, B_d and B_s, but not yet in D^0
- Charm mixing is slower than B or K mixing
- Use $D^* \rightarrow D^0 \pi^+$ to tag the original flavor as D^0 or *anti-*D^0
  - $D^0 \rightarrow K^- \pi^+$, Cabibbo Favored (CF)
  - $D^0 \rightarrow K^+ \pi^-$, Doubly Cabibbo Suppressed (DCS)



D^0 Mixing Belle and BaBar

- Reminder
  - $y = \Delta\Gamma / 2\Gamma$
  - $x = \Delta m / \Gamma$
  - $y' = y\cos\delta - x\sin\delta$
  - δ = strong phase difference between CF and DCS amplitudes
  - mixing parameter $y_{CP} = \tau(D^0 \to K^-\pi^+) / \tau(D^0 \to K^+K^-)$
  - in CP conservation limit $y_{CP} = y$

- Belle

  hep-ex/0703036

  - 540 fb^{-1}
  - y_{CP} = 1.31 ± 0.32 (stat) ± 0.25 (syst) %
  - more than 3σ above zero

- BaBar

  hep-ex/0703020

  - 384 fb^{-1}
  - y' = 0.97 ± 0.44 (stat) ± 0.31 (syst) %
  - 3.9σ deviation from zero

- Evidence for D^0 mixing