Heavy Flavor Physics At the Tevatron

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Aspen Winter Conference

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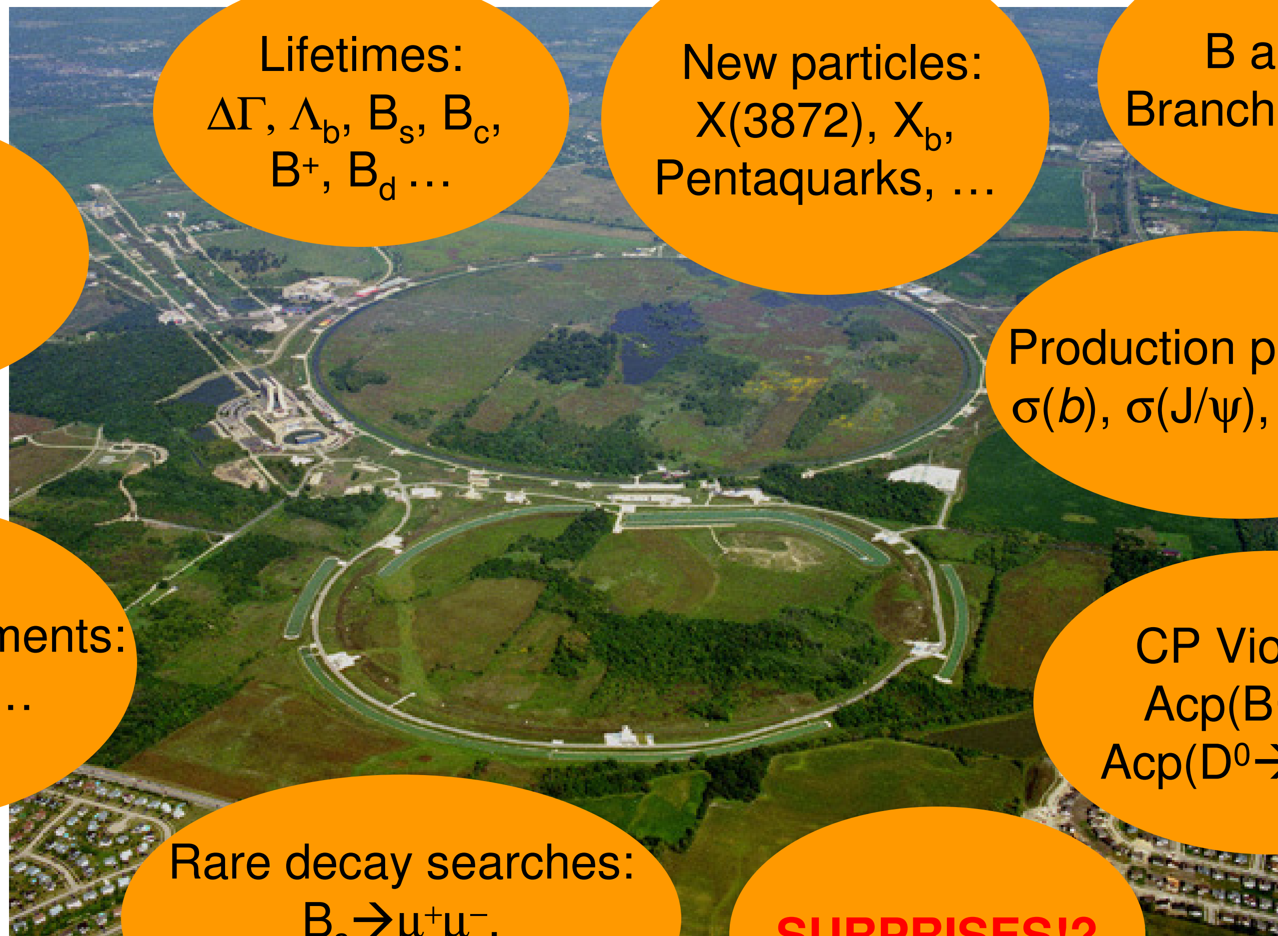
Gold Mine for Heavy Flavor Physics



Lifetimes:
$\Delta\Gamma$, Λ_b, B_s, B_c,
B^+, B_d …

New particles:
X(3872), X_b,
Pentaquarks, …

B and D
Branching ratios

Mixing:
B_s, B_d, D^0

Production properties:
$\sigma(b)$, $\sigma(J/\psi)$, $\sigma(D^0)$, …

Mass measurements:
B_c, Λ_b, B_s, …

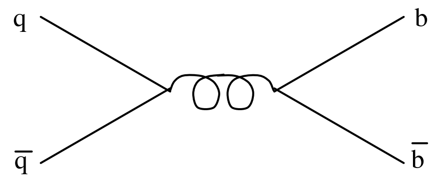
CP Violation:
$Acp(B \rightarrow hh)$,
$Acp(D^0 \rightarrow K\pi)$, …

Rare decay searches:
$B_s \rightarrow \mu^+\mu^-$,
$D^0 \rightarrow \mu^+\mu^-$, …

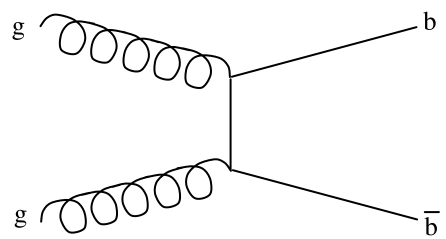
SURPRISES!?

Exciting time at the Tevatron for heavy flavor physics!!!

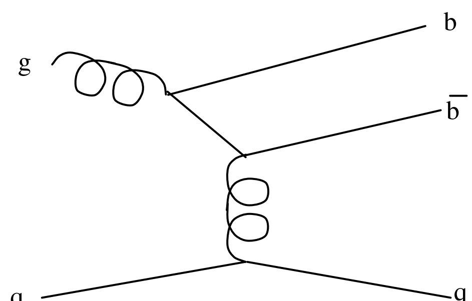
Heavy Flavor Physics In Hadron Environment



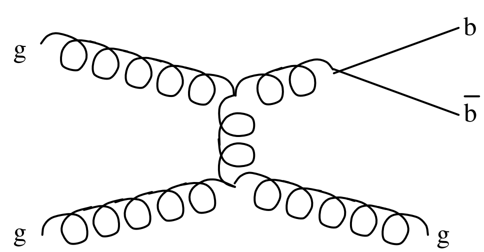
Flavor Creation (annihilation)



Flavor Creation (gluon fusion)



Flavor Excitation



Gluon Splitting

b's produced via strong interaction

decay via weak interaction

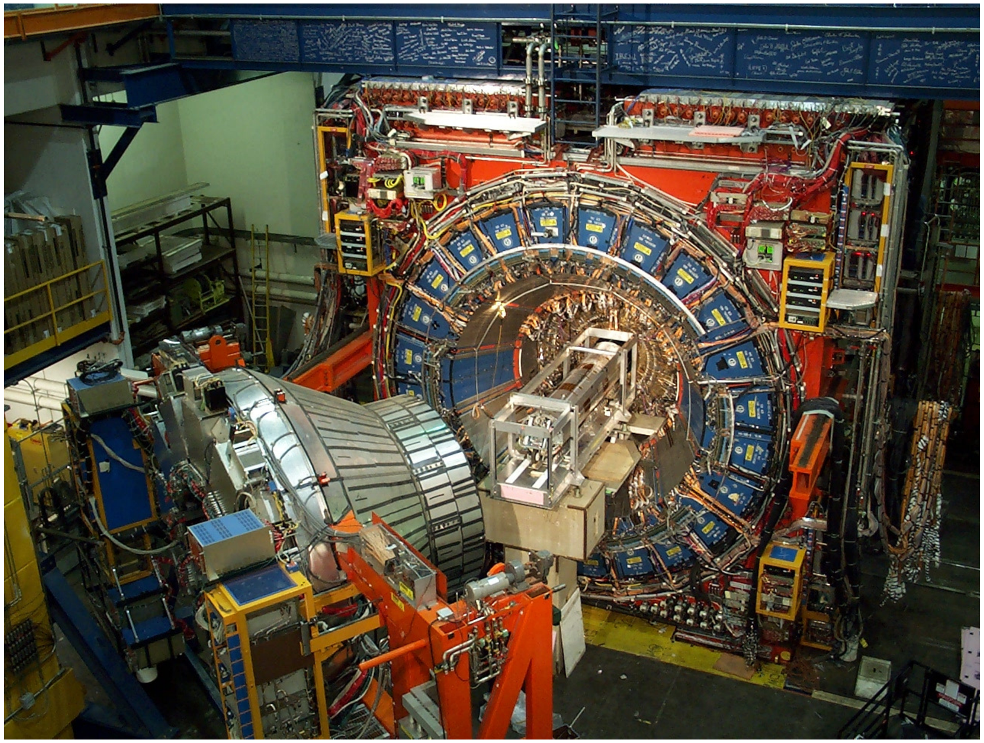
Tevatron is great for heavy flavor:

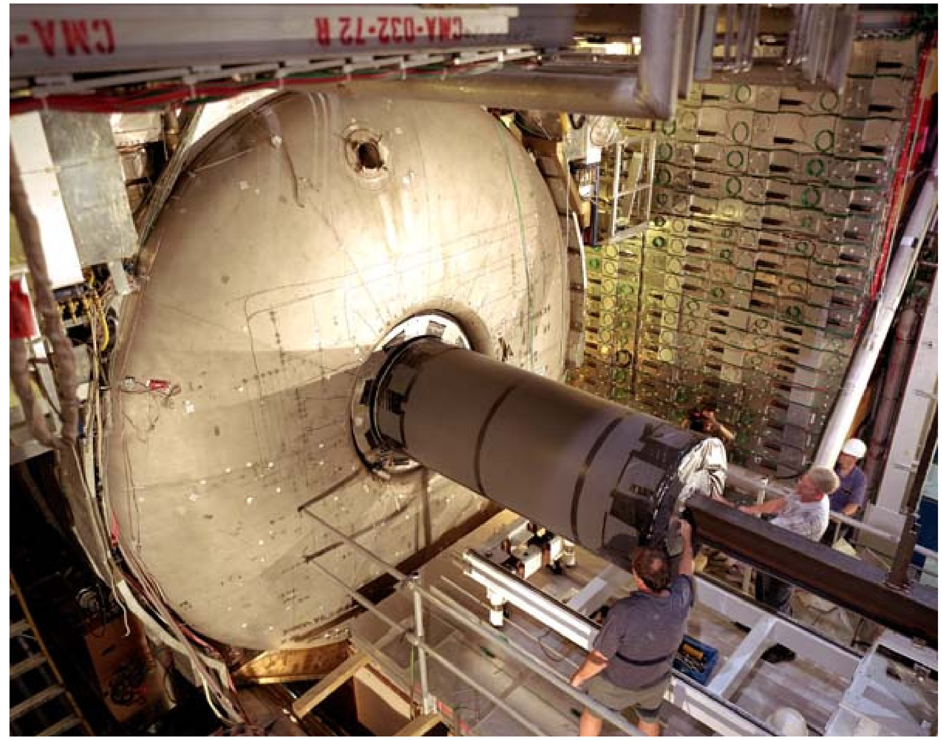
- Enormous *b* production cross-section, x1000 times larger than e^+e^- B factories
- All B species are produced (B^0, B^+, Λ_b, B_s, etc…)

However,

- Inelastic (QCD) background is about x1000 larger than b cross-section
- Online triggering and reconstruction is a challenge: collision rate ~1MHz → tape writing limit ~100Hz

CDF and D0 Detectors





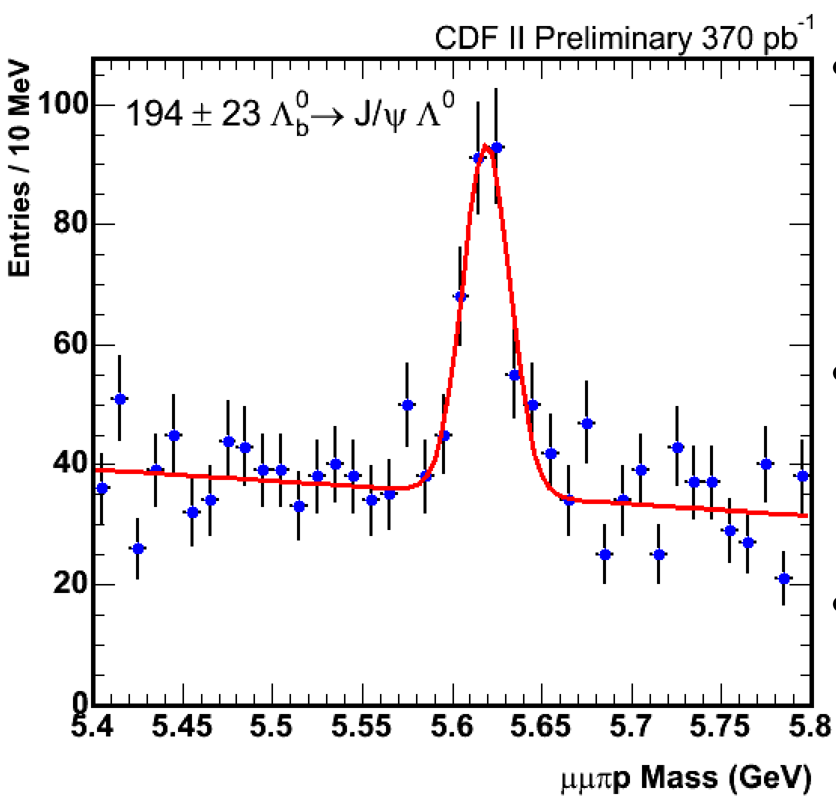
CDF:
- Excellent silicon vertex detector
- Good particle identification (K,π)
- Good momentum and mass resolutions

D0:
- Extended tracking and muon coverage
- Good electron identification
- New innermost-layer silicon detector will be installed in March

Λ_b Lifetime

- Lifetime measurements are important tests of Heavy Quark Expansion (HQE)

- Long standing ~2σ effect between theory and experiment on $\tau(\Lambda_b)/\tau(B^0)$. Experiment on the low side



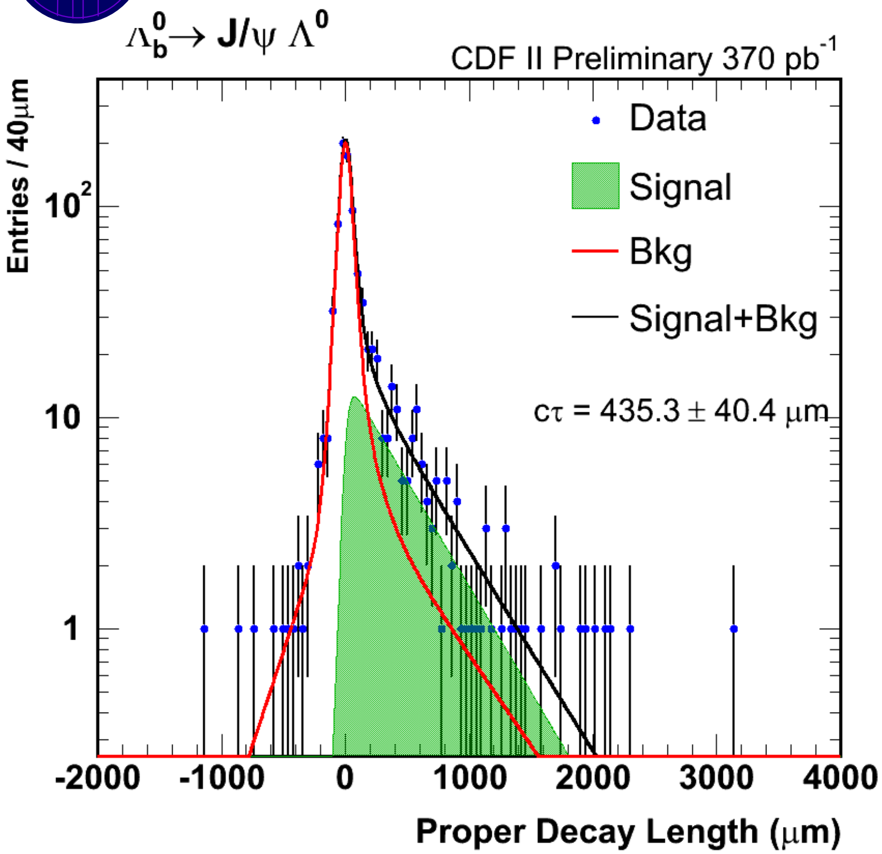
- CDF + D0 has measured the Λ_b lifetime using fully reconstructed

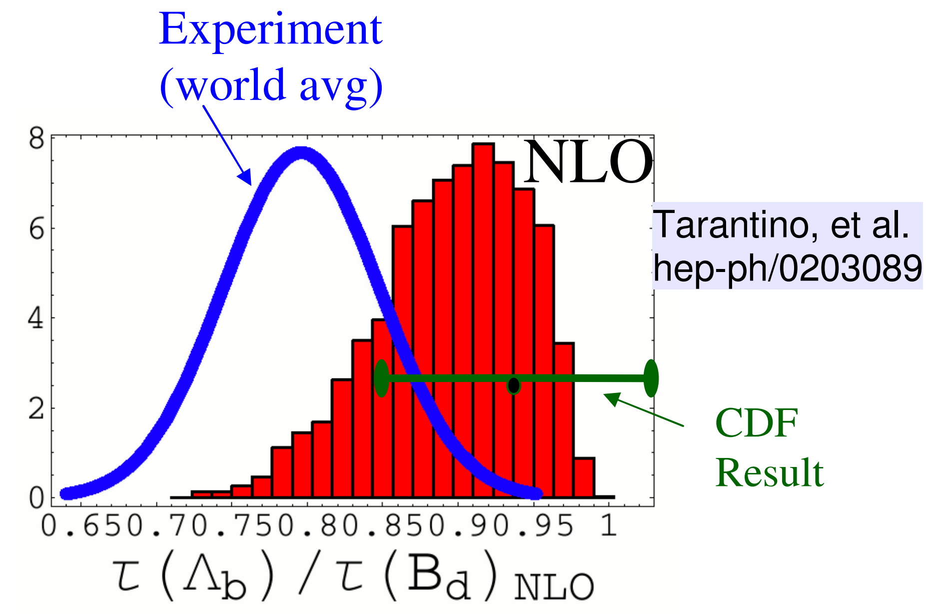
  $\Lambda_b \rightarrow J/\psi\ \Lambda$

- Better proper time resolution than semileptonic mode

- Combine with $\Lambda_c\pi$ channel, Tev has the largest fully reconstructed Λ_b sample in the world

Λ_b Lifetime





- Active theoretical work to accommodate data
- CDF's new result sits in the theory preferred region
- Need more experimental inputs to resolve the issue

CDF (370pb^{-1}):

$$\tau(\Lambda_b) = 1.45^{+0.14}_{-0.13}(stat) \pm 0.02(syst)\,ps$$

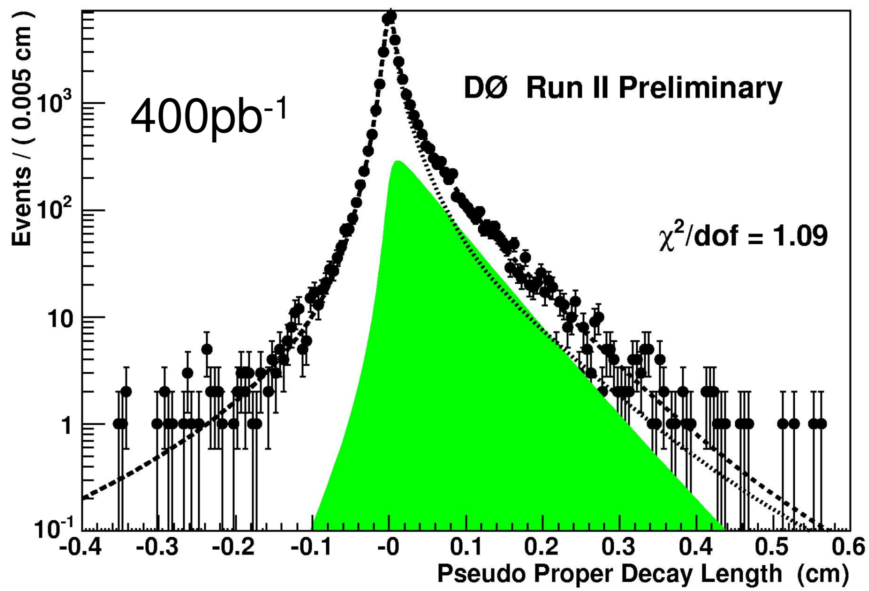
D0 (250pb^{-1}):

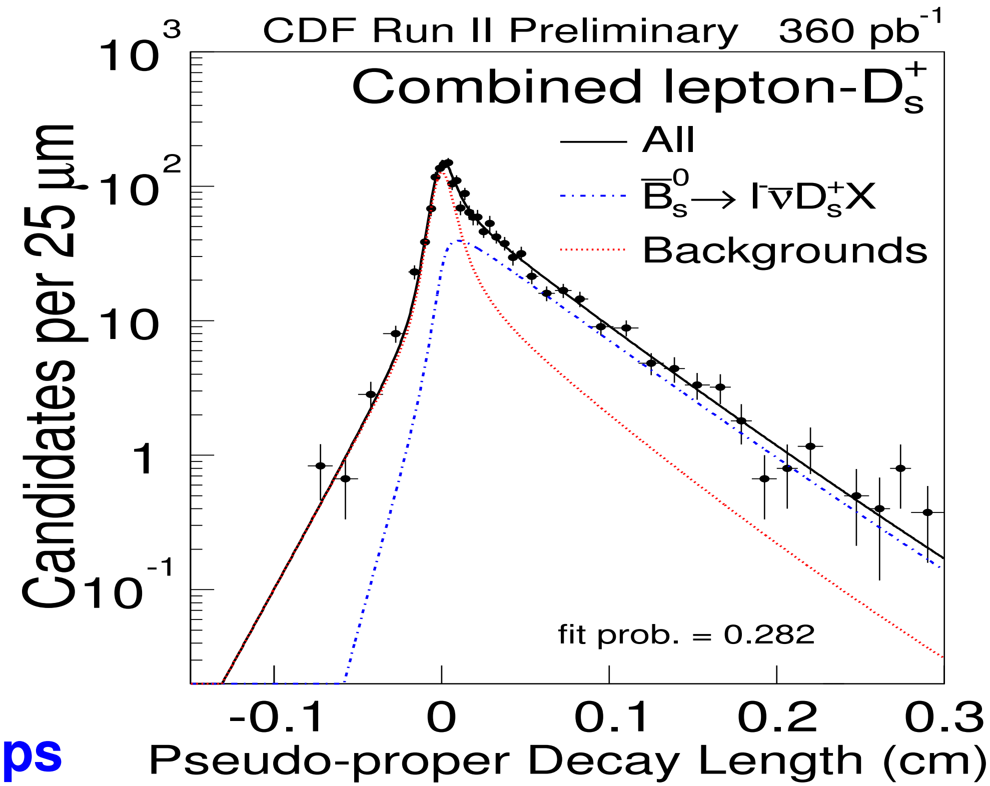
$$\tau(\Lambda_b) = 1.22^{+0.22}_{-0.18}(stat) \pm 0.04(syst)\,ps$$

PRL 94 102001 (2005)

B_s Lifetime

D0 and CDF measure B_s lifetime in semileptonic decay: $B_s \rightarrow l^+ \nu D_s^- X$





D0:

$\tau(B_s)$=1.420±0.043(stat) ±0.057(syst) ps

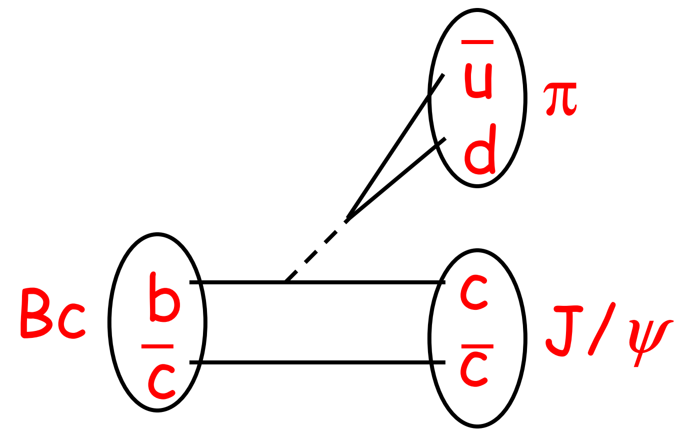
(Best in the world)

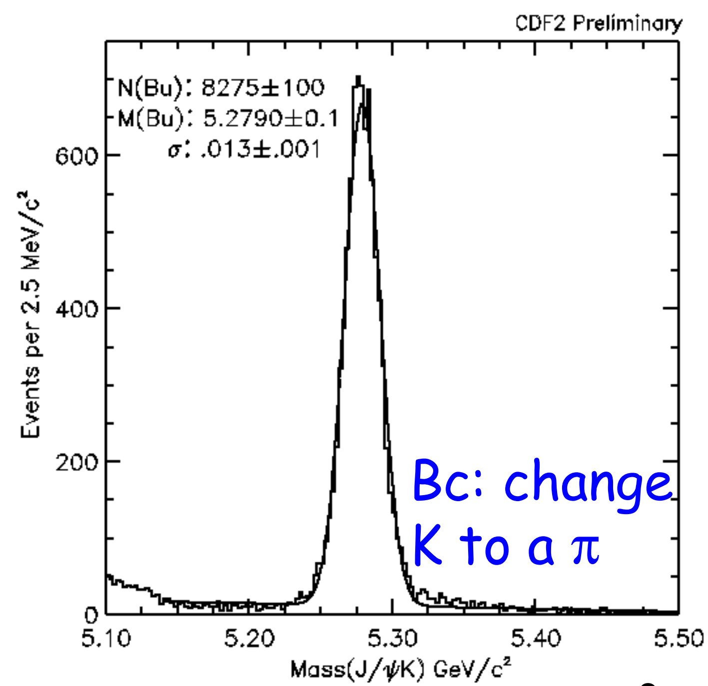
CDF:

$\tau(B_s)$=1.381±0.055(stat) $\pm^{0.052}_{0.046}$(syst) ps

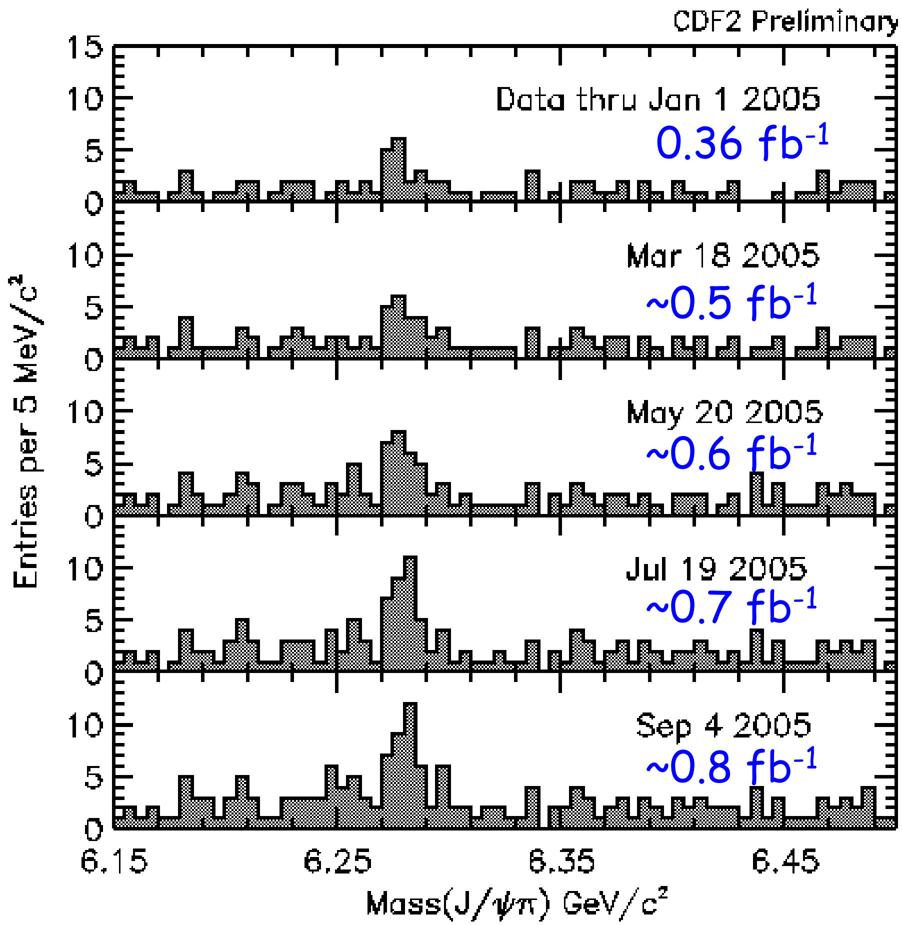
B_c Mass Measurement

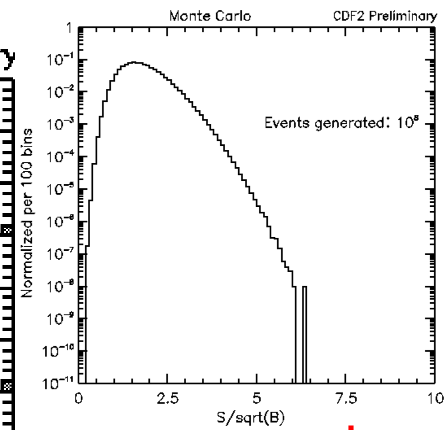
- B_c has short lifetime and small production rate
- Full reconstruction allows for precise mass measurement
- New CDF analysis
  - Tune B_c selection on reference $B^+ \rightarrow J/\psi K^+$ data
  - After selection cuts are fixed, "open box"
  - Wait for events to become a significant excess
  - Measure properties of the B_c





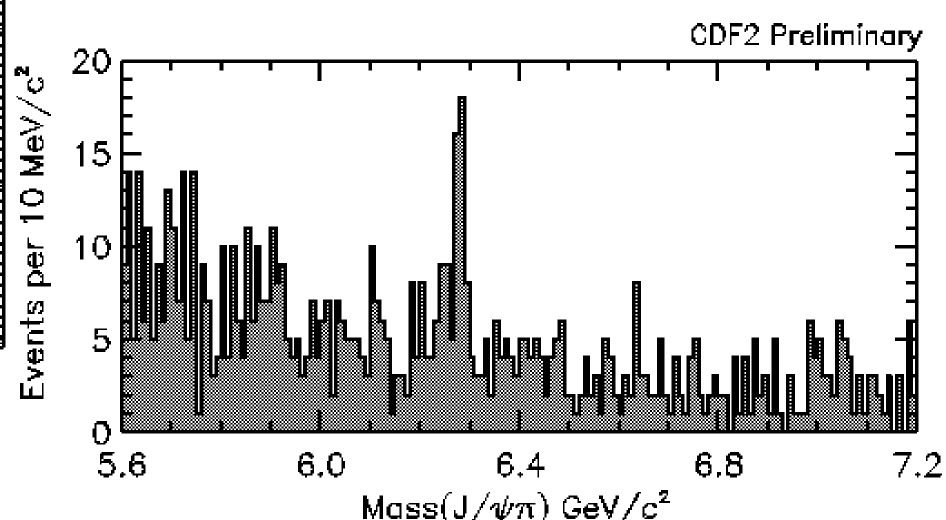
B_c Mass Measurement





Num(events)$_{FIT}$=
38.9 sig 26.1 bkg
between 6.24-6.3

Significance > 6σ
over search area

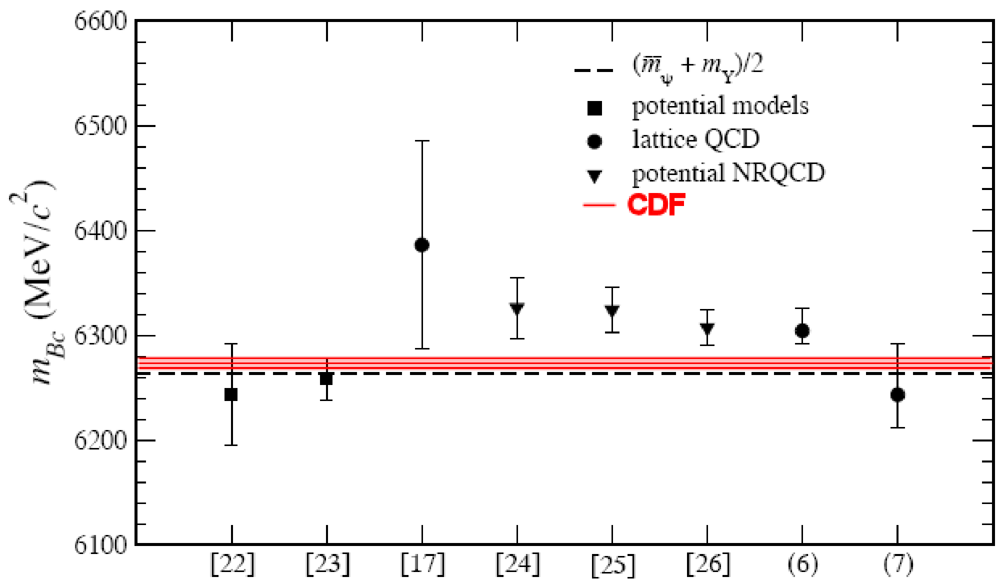


Mass(Bc) = 6275.2 +/- 4.3 +/- 2.3 MeV/c^2

Most precise measurement of Bc mass

B_c Lattice Calculations

- Recent lattice calculations predict B_c mass with ~20 MeV precision !!



$M(Bc)_{CDF} = 6275.2 \pm 4.3 \pm 2.3\ MeV/c^2$ (hadronic)

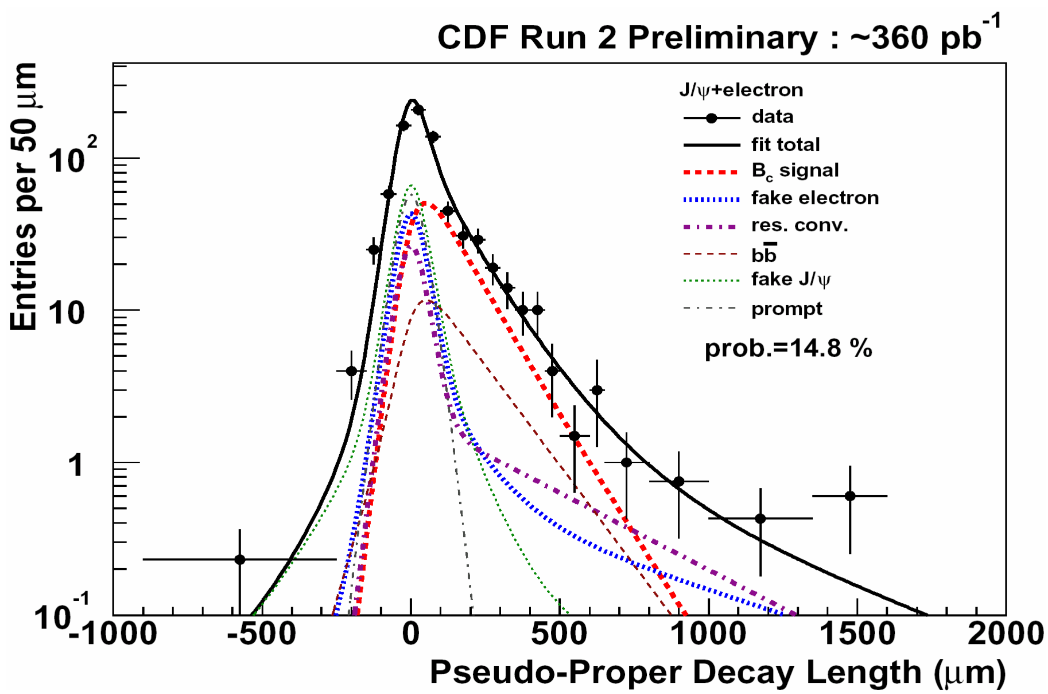
$M(Bc)_{D0} = 5950 \pm 140 \pm 340\ MeV/c^2$ (semileptonic)

$M(Bc)_{LAT} = 6304 \pm 12\ ^{+18}_{-0}\ MeV/c^2$

I.F. Allison et al., PRL 94 172001 (2005)

B_c Lifetime

- Bc lifetime extracted from $B_c \rightarrow J/\psi\ e\ \nu$ sample



- More stat than hadronic mode
- But also more background too

- CDF B_c lifetime measured with J/ψ+e channel ($360pb^{-1}$)
  0.474 +0.074/-0.066 ±0.033 ps (Best in the world)
- D0 B_c lifetime measured with $J/\psi+\mu$ channel ($210pb^{-1}$)
  0.448 +0.123/-0.096 ±0.121 ps
- Theoretical prediction: 0.55 ± 0.15 ps V. Kiselev, hep-ph/0308214

Review of B^0 System

- In the B^0 system: physical mass eigenstates ≠ flavor eigenstates

$$|B_L\rangle = |B^0\rangle + |\overline{B}^0\rangle$$

$$|B_H\rangle = |B^0\rangle - |\overline{B}^0\rangle \quad \text{(ignoring CP violation)}$$

- Time evolution of the two states is governed by the time-dependent Schrödinger equation and in the limit $\Delta\Gamma \ll \Delta m$:

$$\mathrm{Prob}\,(B^0 \to B^0) = \frac{1}{2} e^{-\Gamma t}\left(1 + \cos \Delta m t\right)$$

$$\mathrm{Prob}\,(B^0 \to \overline{B}^0) = \frac{1}{2} e^{-\Gamma t}\left(1 - \cos \Delta m t\right)$$

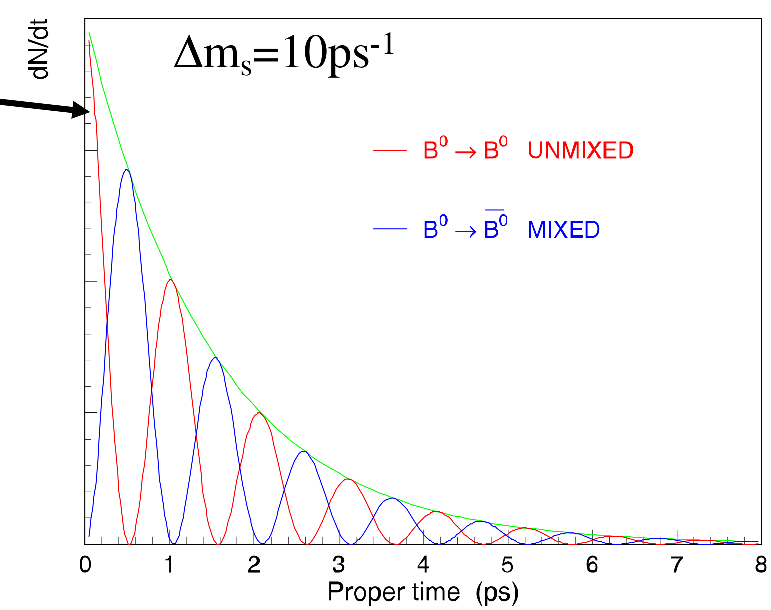
where: $\Delta\Gamma = \Gamma_H - \Gamma_L$ (lifetime difference)

$\Gamma = (\Gamma_H + \Gamma_L)/2$

$\Delta m = m_H - m_L$ (mass difference)

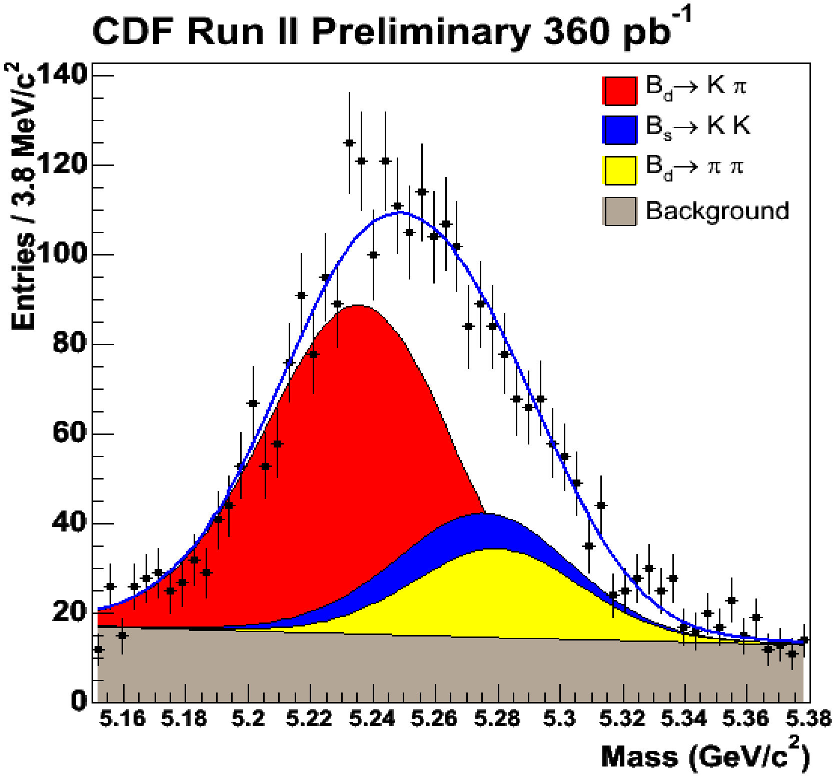
oscillation frequency

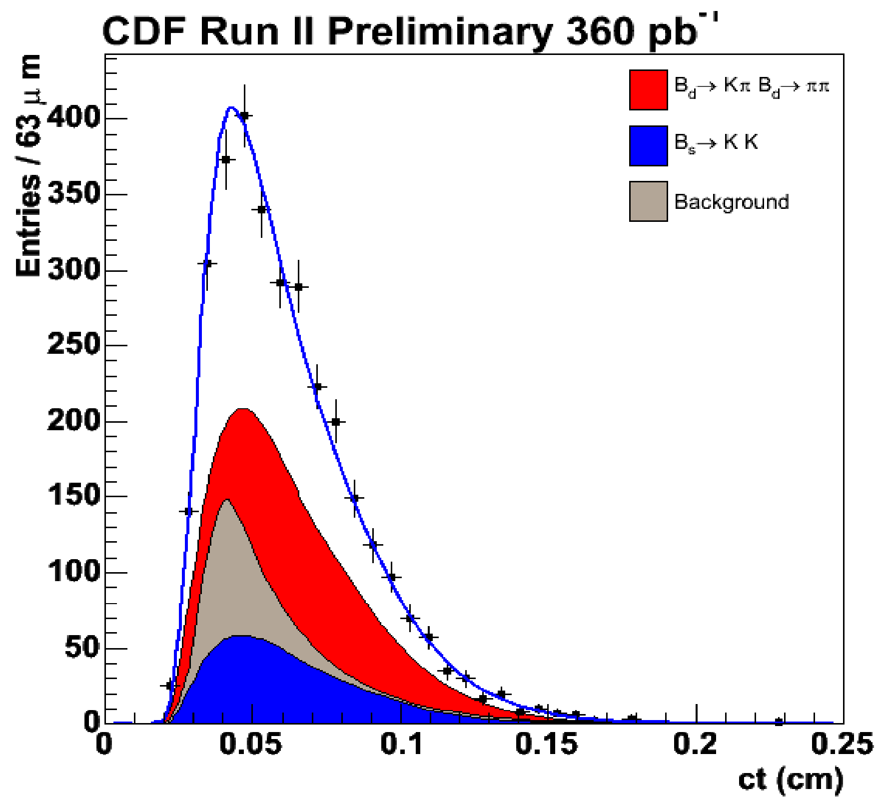
($B_d \Rightarrow \Delta m_d$, $B_s \Rightarrow \Delta m_s$)



Extract $\Delta\Gamma$ from $B_s \rightarrow K^+ K^-$ Lifetime

- Measurement of $B_s \rightarrow K^+K^-$ lifetime ($=\tau_L$) in 360pb^{-1}
- Mass fit as in BR and CP measurements
- Lifetime fit:





- Extraction of $\Delta\Gamma(CP)/\Gamma(CP)$
  - This measurement gives $c\tau_L = 458 \pm 53 \pm 6\ \mu m$
  - HFAG average gives weighted average: $(\tau_L^2 + \tau_H^2)/(\tau_L + \tau_H)$
  - Extract τ_H
  - Thus derive $\Delta\Gamma/\Gamma = -0.080 \pm 0.23\ (stat) \pm 0.03\ (syst)$

Summary of $\Delta\Gamma_s / \Gamma_s$ Measurements

- **CDF $B_s \rightarrow K^+K^-$ (measure τ_L): 360pb^{-1}**

  $\Delta\Gamma/\Gamma = -0.080 \pm 0.23\,(\text{stat}) \pm 0.03\,(\text{syst})$

- **D0 $B_s \rightarrow J/\psi\,\phi$ (measure τ_H, τB_s): 220pb^{-1}**

  $\Delta\Gamma/\Gamma = 0.24 \pm^{0.28}_{0.38}(\text{stat}) \pm^{0.03}_{0.04}(\text{syst})$

  PRL 95 171801 (2005)

- **CDF $B_s \rightarrow J/\psi\phi$ (measure τ_L and τ_H): 210pb^{-1}**

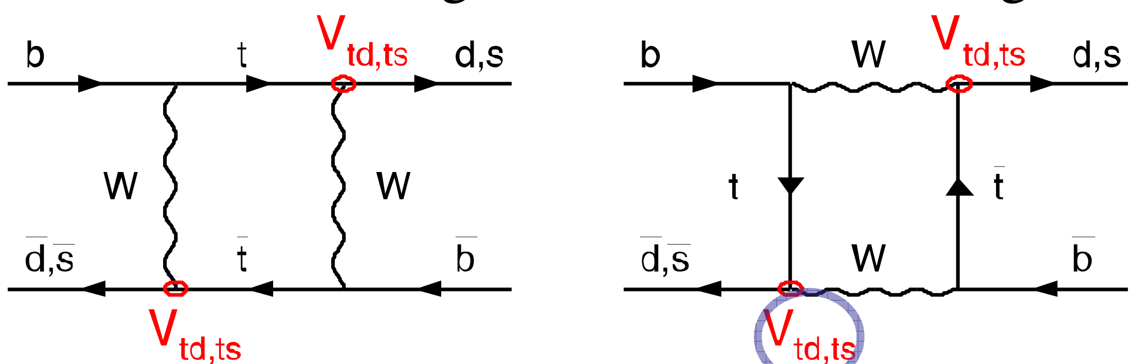
  $\Delta\Gamma/\Gamma = 0.65 \pm^{0.25}_{0.33}(\text{stat}) \pm 0.01\,(\text{syst})$

  PRL 94 102001 (2005)

Both CDF and D0 have >x2 more data to analyze

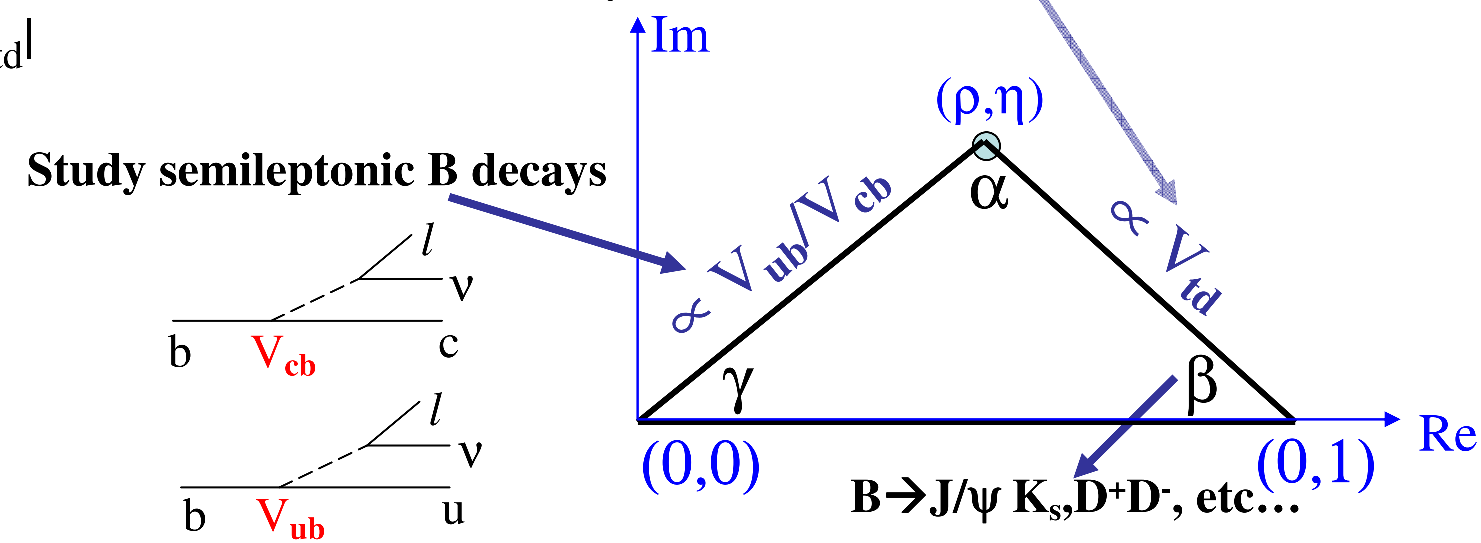
$B_s^0 - \overline{B}_s^0$ Oscillations

- In the Standard Model B mixing occurs via the box diagram:



- Study of B^0 oscillation provides an important test of SM and probes the origin of CP violation

- A measurement of B^0 oscillation frequency, specifically Δm_d, is the most direct way to extract $|V_{td}|$



$B_s^0 - \overline{B}_s^0$ Oscillations

- Δm_d has been measured to within ~1% ($\Delta m_d = 0.507 \pm 0.004 ps^{-1}$, HFAG2005)
  However, extraction of $|V_{td}|$ is severely limited by theoretical uncertainties:

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_t^2 \, F\left(\frac{m_t^2}{m_W^2}\right) B_{B_d} f_{B_d}^2 \eta_{QCD} \left| V_{tb}^* V_{td} \right|^2$$

~15% uncertainty on $\sqrt{B_{B_d}} f_{B_d}$

- The problem can be circumvented by measuring Bs mixing.
  Dominant theoretical uncertainties cancel in the ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \cdot \left| \frac{V_{ts}}{V_{td}} \right|^2 = \frac{m_{Bs}}{m_{Bd}} \xi^2 \cdot \left| \frac{V_{ts}}{V_{td}} \right|^2$$

(assume $V_{ts} = V_{cb}$)

New lattice result $\xi = 1.21^{+0.041}_{-0.026}$ (~3% uncertainty)

- Sounds like a good approach to measure $|V_{td}|$, but…
  Δm_s is expected to be large (much larger than Δm_d)

Key Ingredients of Bs Mixing Analysis

1. Enriched sample of B_s^0 decays
2. Determine the flavor of B_s^0 at production and decay
3. Reconstruct the decay length & boost of the $B_s^0 \rightarrow$ proper decay time $\left(t = L/\beta\gamma c\right)$

The significance of the analysis can be estimated using the Moser formula:

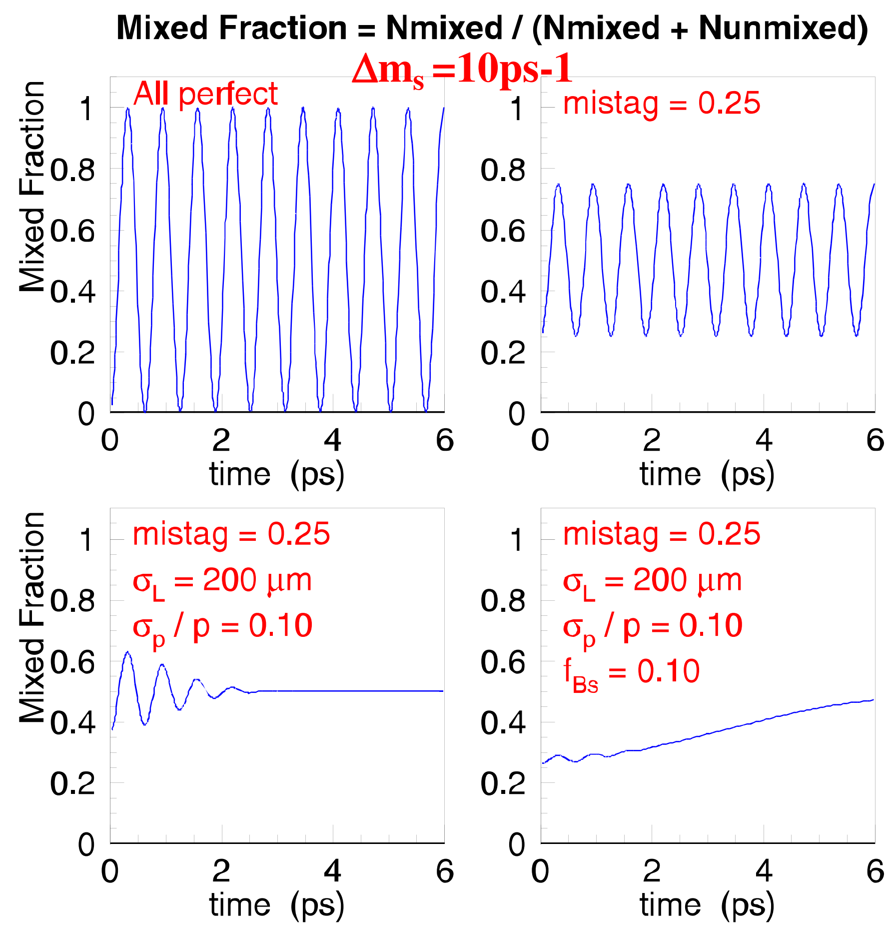
$$\text{Significance} = \sqrt{\frac{N\varepsilon D^2}{2}}\, f_{B_s}\, e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2}$$

- N = # of events
- f_{Bs} = Bs fraction
- εD^2 = flavor tagging power
- σ_t = proper time resolution

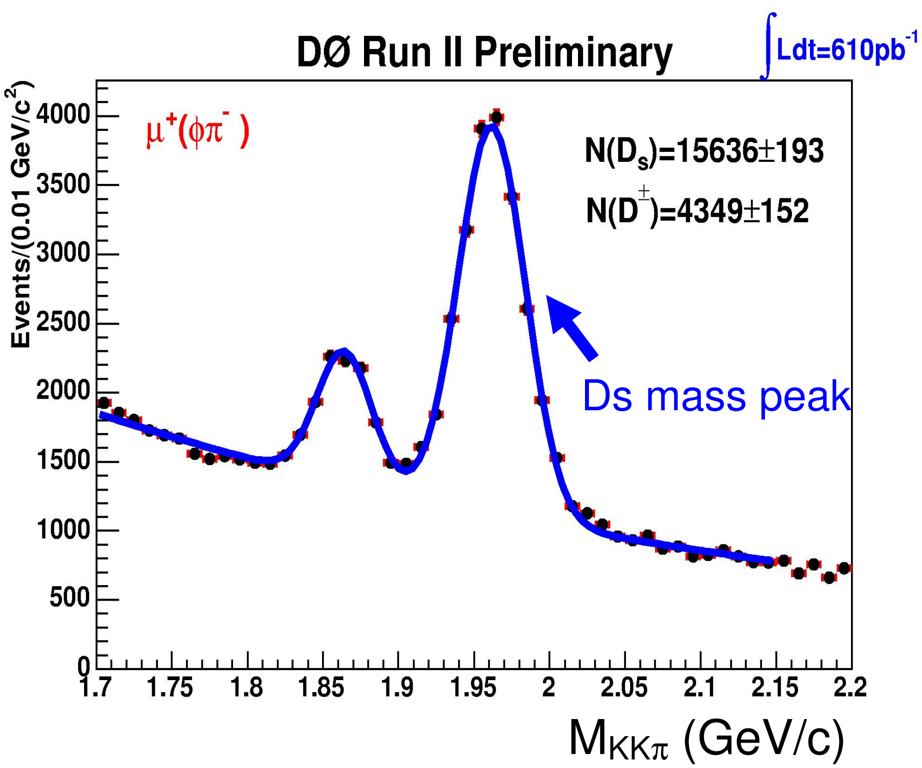
Proper time resolution has contribution from decay length and boost

$$\sigma_t^2 = \left(\frac{\sigma_L}{\gamma\beta c}\right)^2 + \left(\frac{\sigma_p}{p}t\right)^2$$

constant — grows linearly with proper time

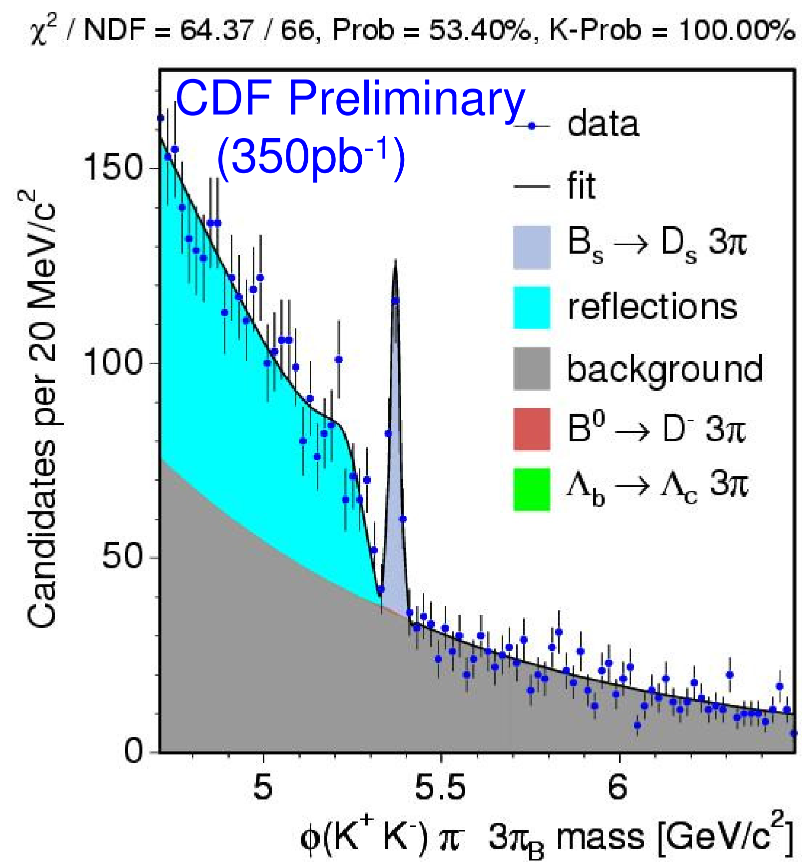


B_s Signal Sample



$B_s \rightarrow D_s\, \mu\, \nu$ (where $D_s \rightarrow \phi\pi$, $K^* K$)

~34K semileptonic B_s (610pb^{-1})



$B_s \rightarrow D_s\, \pi$ (where $D_s \rightarrow \phi\pi$, $K^* K$, 3π)

$B_s \rightarrow$ Ds 3π (where $D_s \rightarrow \phi\pi$, $K^* K$)

~1100 fully reconstructed B_s

~17K semileptonic B_s (350pb^{-1})

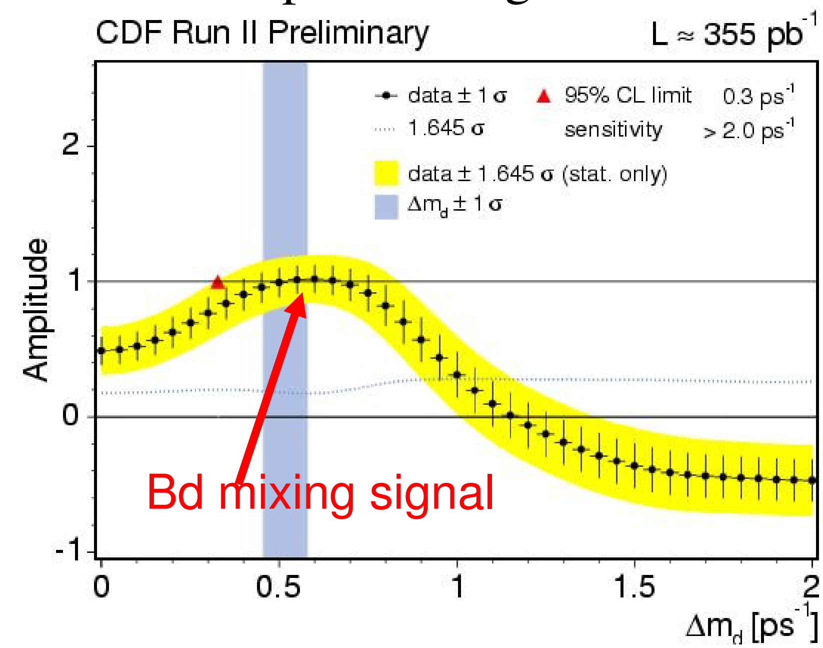
Amplitude Fit Primer

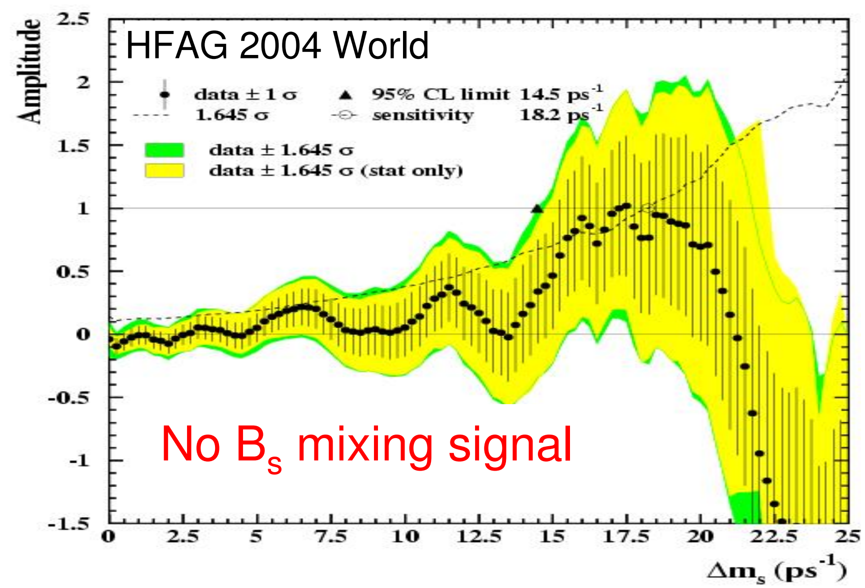
- A modified form of Fourier analysis is used to search for periodic signal
  $\Rightarrow$ Amplitude Fit (NIM A384, 491 (1997))

- Amplitude fit :
  - $\text{Prob}\,(B_s^0 \rightarrow B_s^0) = \frac{1}{2}\Gamma e^{-\Gamma t}(1 + A\cos\Delta m_s t)$

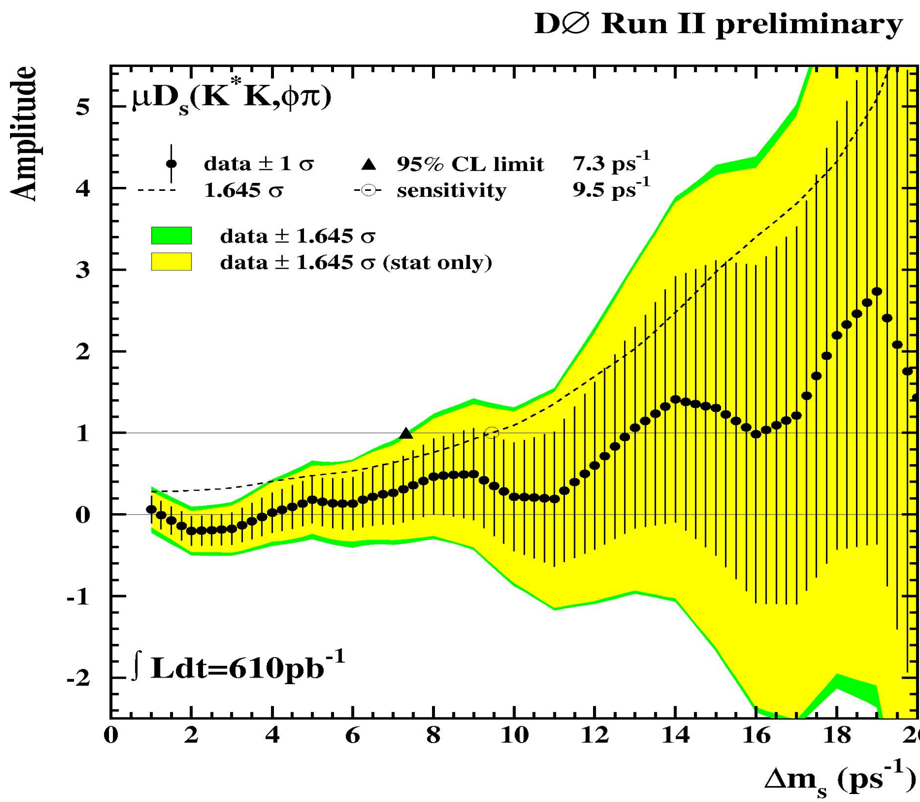
    $\text{Prob}\,(B_s^0 \rightarrow \overline{B}_s^0) = \frac{1}{2}\Gamma e^{-\Gamma t}(1 - A\cos\Delta m_s t)$
  - Fit for oscillation amplitude "A" for a given Δms value
  - Expect "A" = 1 for frequency = true Δms
    Expect "A" = 0 for frequency ≠ true Δms

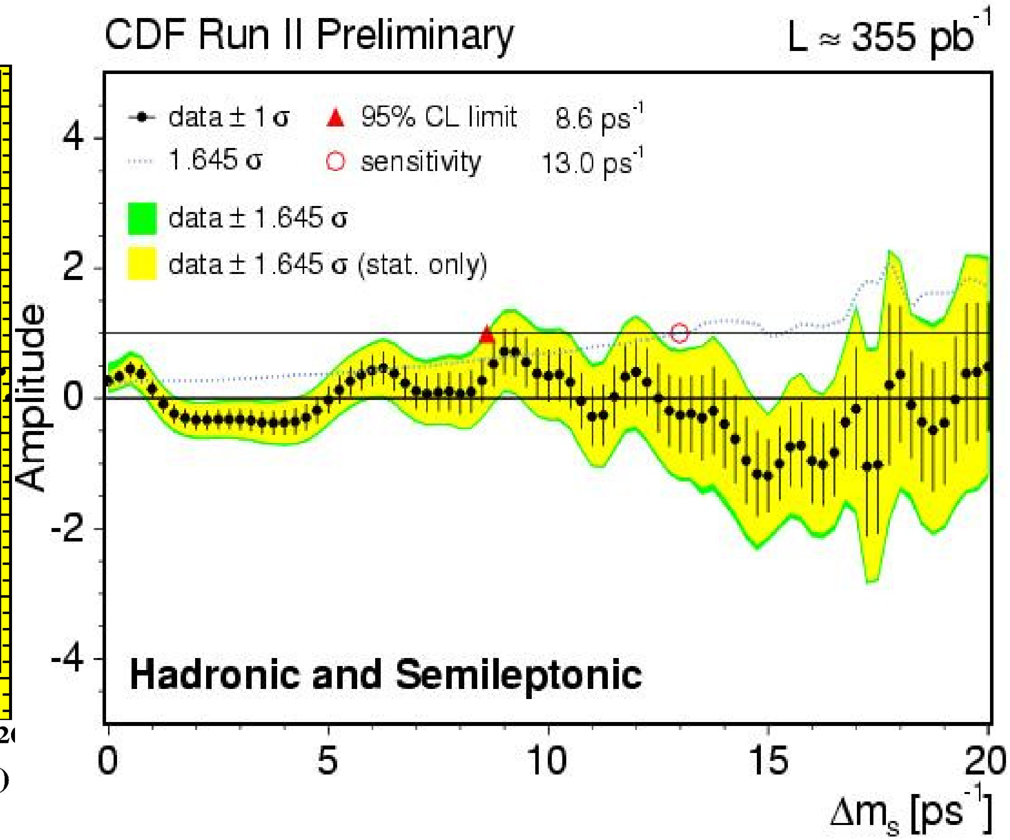
- If no signal is observed:
  - Exclude Δms value at 95% C.L. in regions where $A+1.65\sigma_A < 1$
  - Sensitivity at 95 % C.L. is at Δms value for which $1.65\sigma_A=1$





Amplitude Fit Results





D0 Result:

Sensitivity = 9.5 ps^{-1}

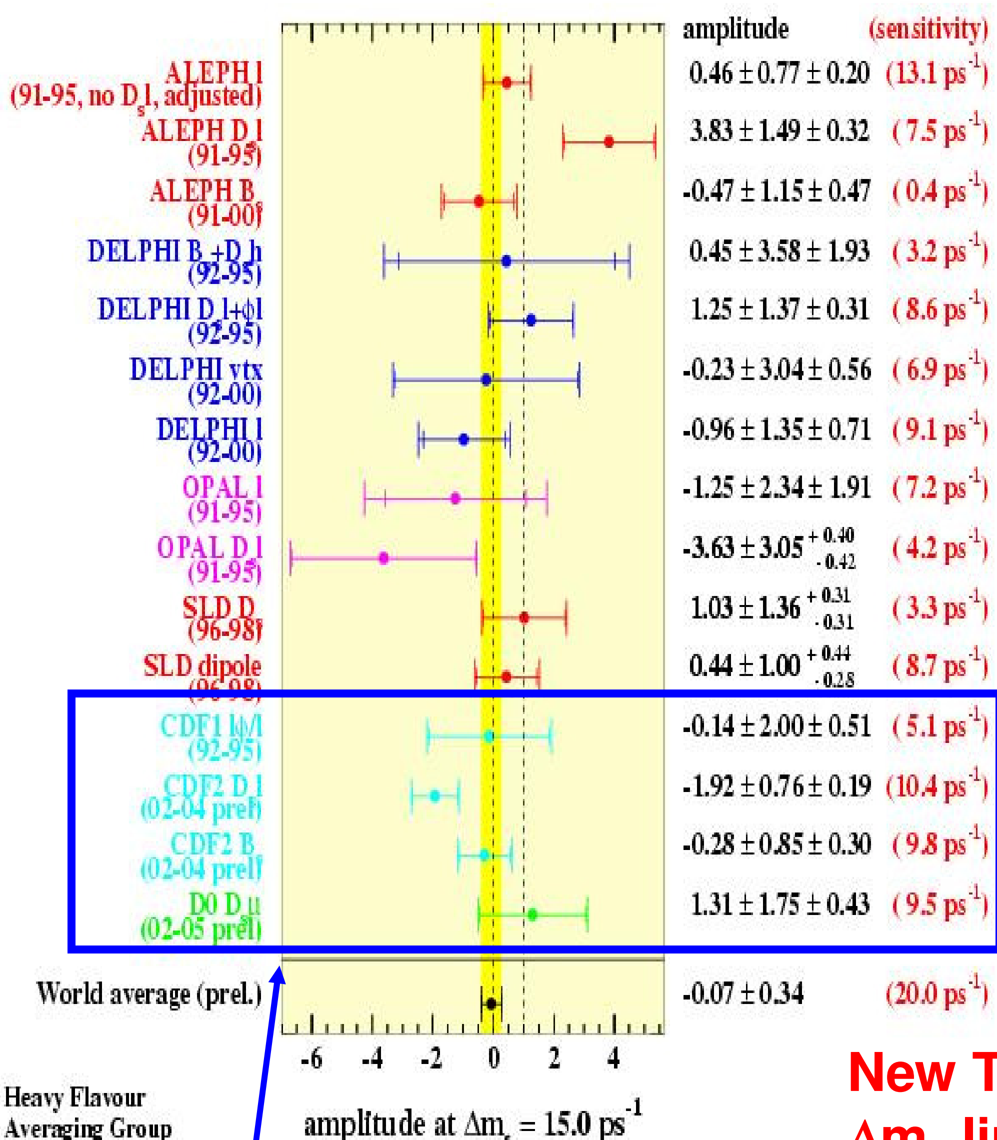
Exclusion: $\Delta m_s < 7.3$ ps^{-1} @95%CL

CDF Result:

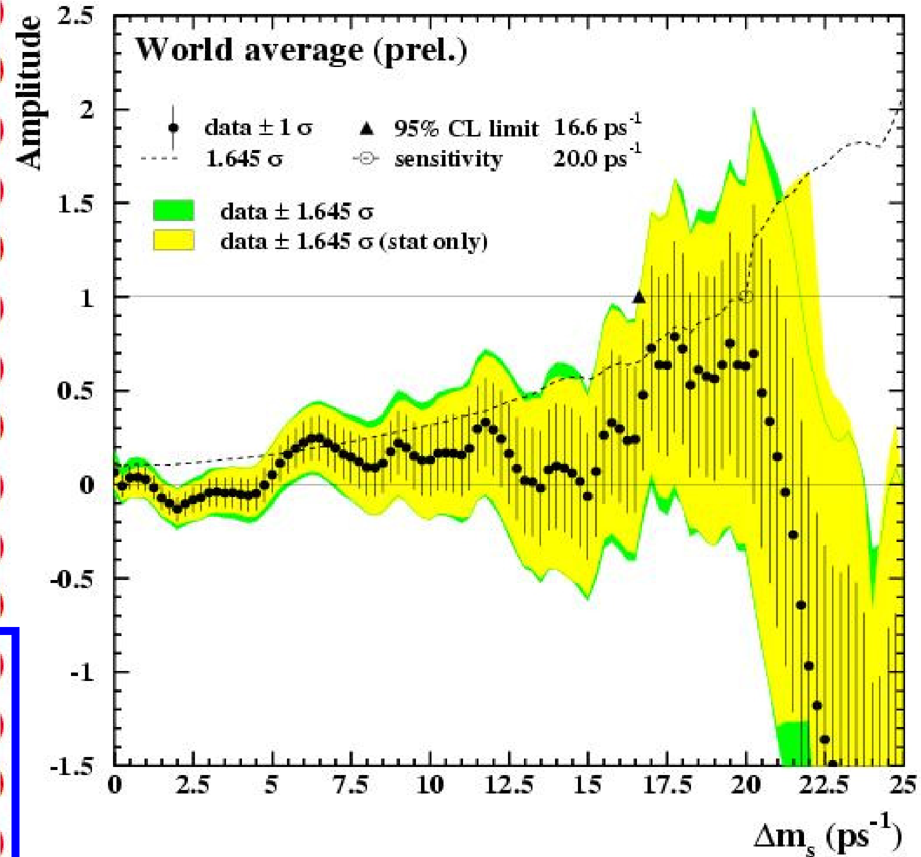
Sensitivity = 13.0 ps^{-1}

Exclusion: $\Delta m_s < 8.6$ ps^{-1} @95%CL

World Average

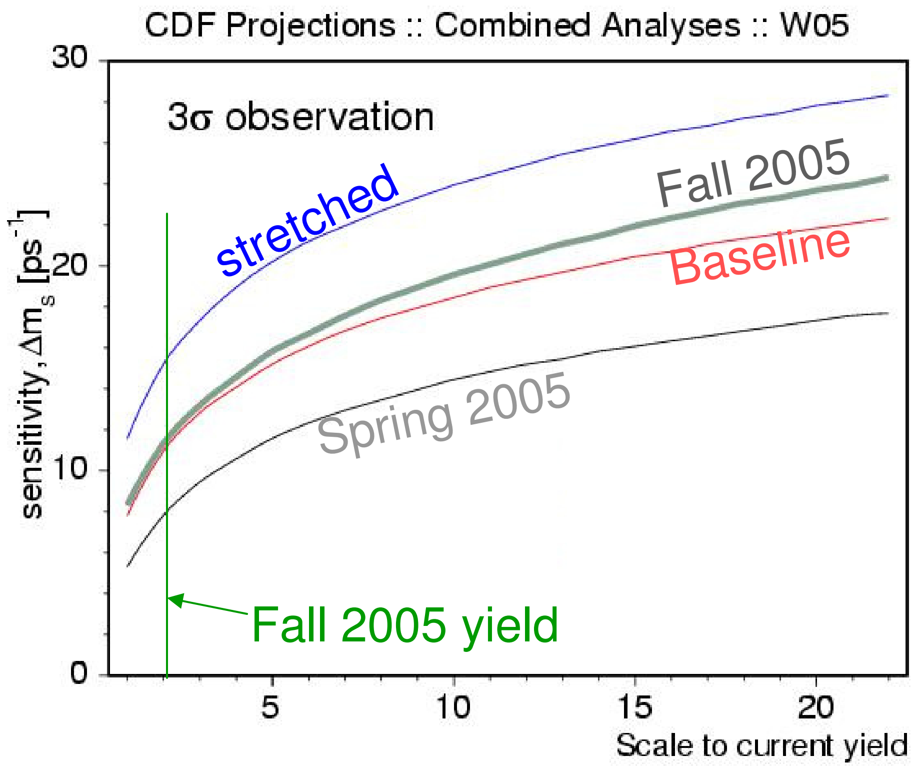


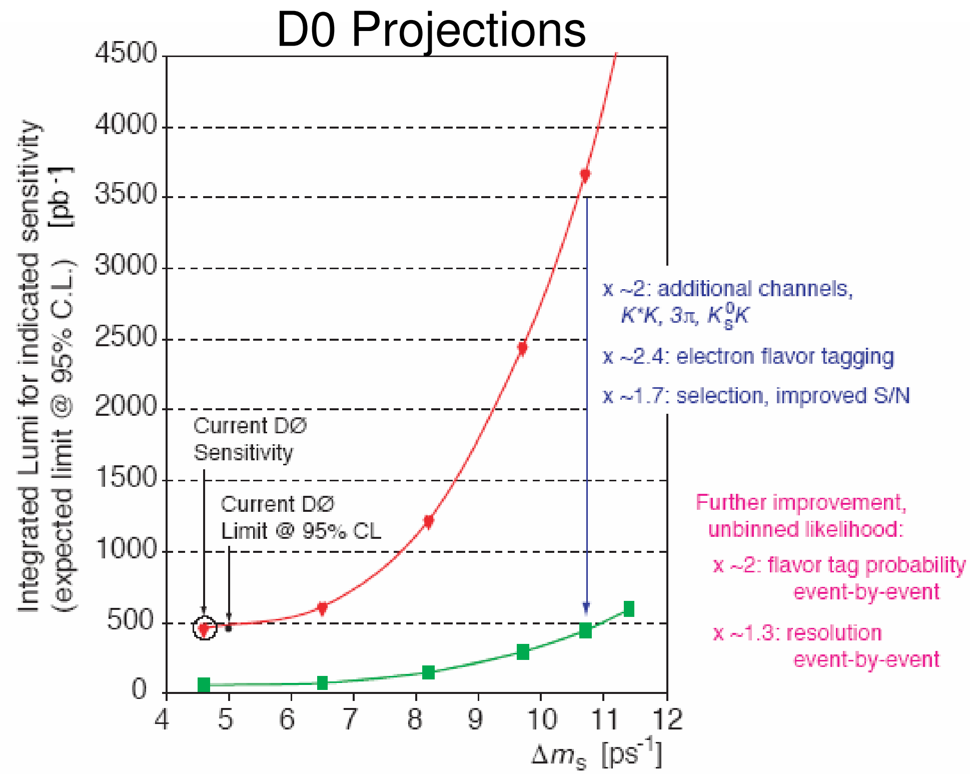
Tevatron contribution



New Tevatron results improved the world Δm_s limit from 14.5 to 16.6 ps^{-1} @ 95%CL

B_s Mixing Projection





- CDF projections were made ~ 1year ago
- CDF has surpassed the baseline projection
- Goal is to reach "stretched" by Sum 2006:
  - Same-side kaon tag
  - Partially reconstructed Bs*→Bs
- At "stretched", CDF will be probing SM region at 3-sigma level this summer

- D0 has an aggressive plan to improve sensitivity:
  - additional modes
  - electron flavor tag
  - evt-by-evt likelihood

Summary

- With 1fb^{-1} of data/experiment, heavy flavor physics at the Tevatron is in full swing. In this talk, I have only touched the "tip of the iceberg"
- Tevatron is entering precision era on measuring a broad spectrum of B and Charm properties. Many measurements are unique to Tevatron and some are complementary to the B-factory physics program
- One exciting prospect this summer: Tevatron will start probing the SM Δm_s regions at 3-sigma level. Tevatron is finally "in the game"
- Stay tuned!!!