Measurements of the Masses, Mixing, and Lifetimes, of B Hadrons at the Tevatron

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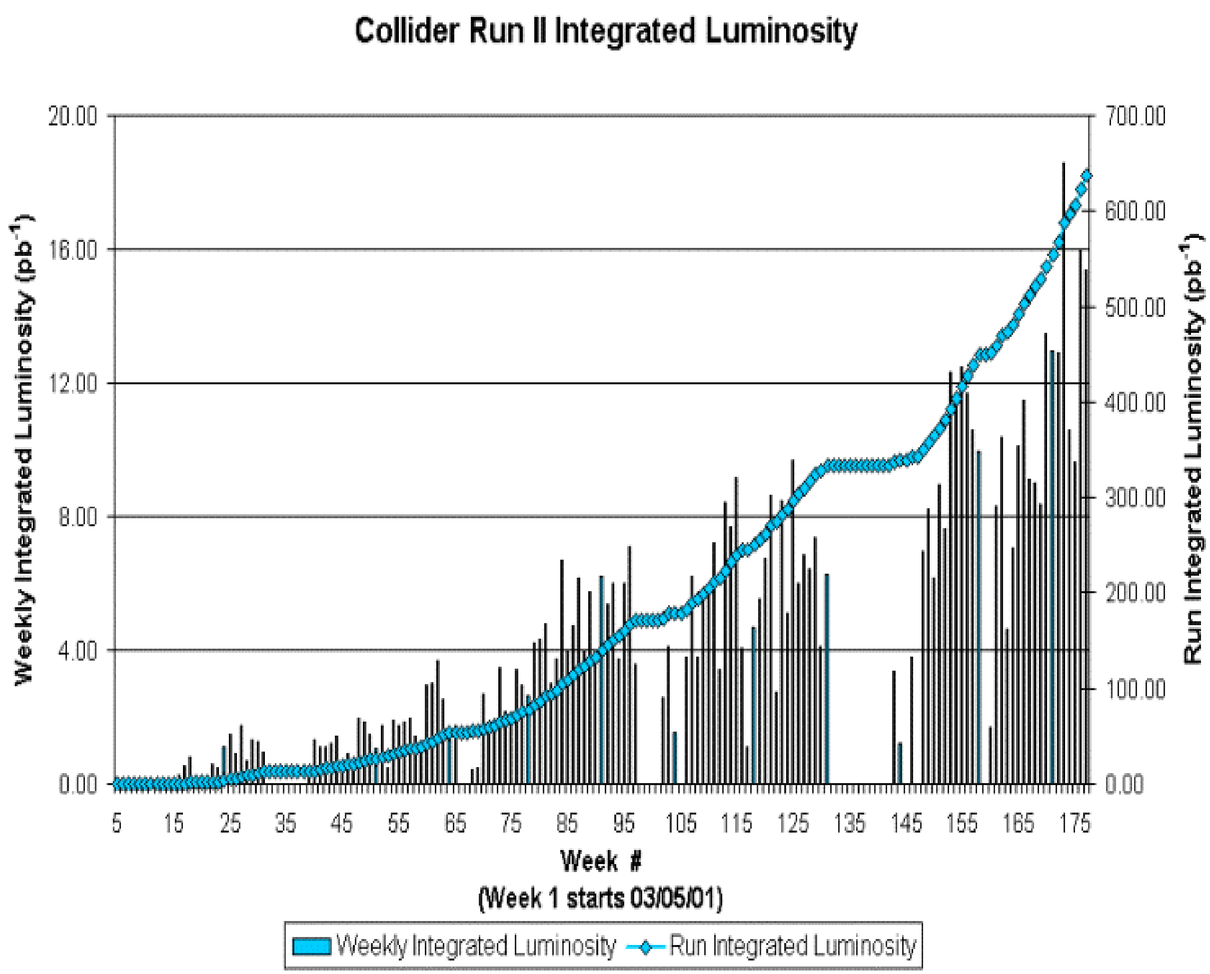
Outline

- *B* Physics at the Tevatron
- *B* Resonances
- B^0 oscillations
- *B* Lifetimes
  - Exclusive Decays
  - Lifetime Ratios and Differences

Tevatron Luminosity



- ~0.3 fb^{-1} delivered this year
- Detectors collect data at typically 85% efficiency
- These analyses use 150–350 pb^{-1}
- About 150 pb^{-1} of data has been recorded but not yet analyzed

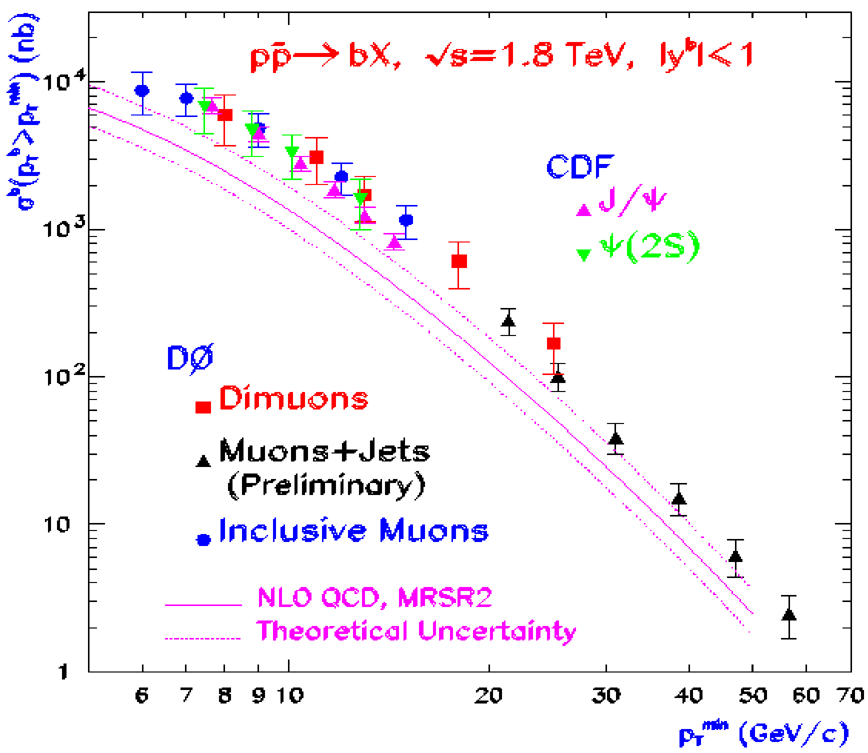
B Physics at the Tevatron

- Large production cross sections
- All *B* Hadrons produced (Best B_s and Λ_b)
- Larger inelastic cross section (S/B ≈ 10^{-3})
- Specialized Triggers:
  - Single lepton triggers
  - Dilepton triggers (e.g. $J/\psi \rightarrow \mu^+\mu^-$)
  - L1 Track triggers
  - L2 displaced track trigger for CDF

$\sigma(p\bar{p} \rightarrow b\bar{b}) \approx 150\ \mu b$ at 2 TeV

$\sigma(e^+e^- \rightarrow b\bar{b}) \approx 7$ nb at Z^0

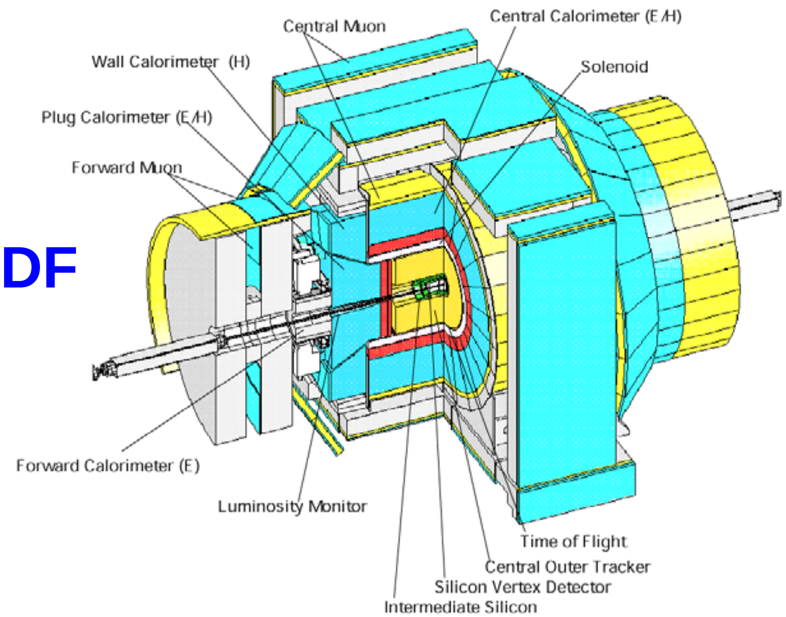
$\sigma(e^+e^- \rightarrow b\bar{b}) \approx 1$ nb at $\Upsilon(4S)$

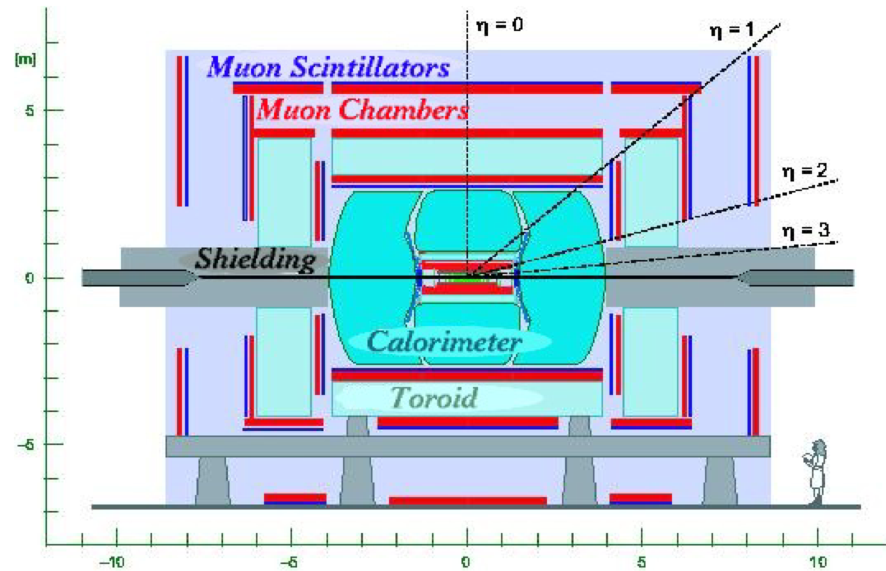


Detectors

Silicon vertex tracker, Axial solenoid, Central tracking,
High rate trigger/DAQ, Calorimeter, Muon system

CDF





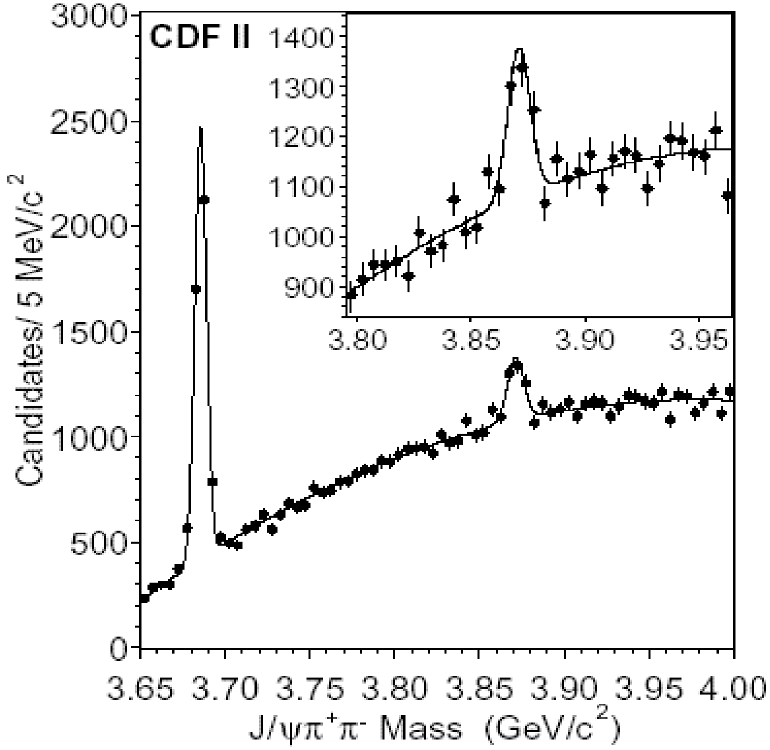
DØ

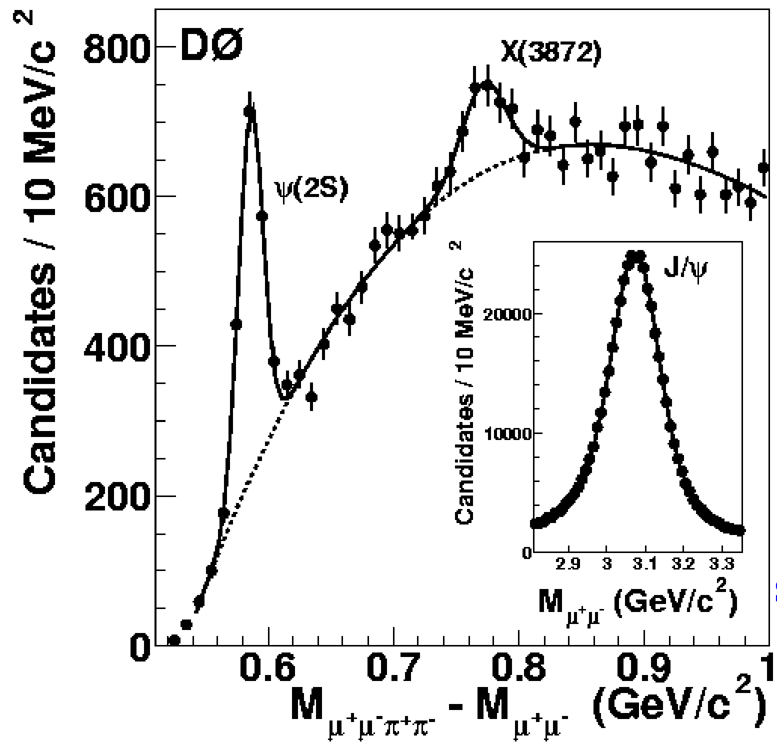
L2 trigger on displaced vertexes
Low *p* particle ID (TOF and dE/dx)
Excellent mass resolution

Excellent muon ID; $|\eta| < 2$
Tracking acceptance $|\eta| < 2\text{-}3$
L3 trigger on impact parameter

$X(3872)$

CDF and DØ have confirmed Belle's discovery of the $X(3872)$





$M_X = 3871.3 \pm 0.7$ (stat) ± 0.4 (sys) MeV/c^2

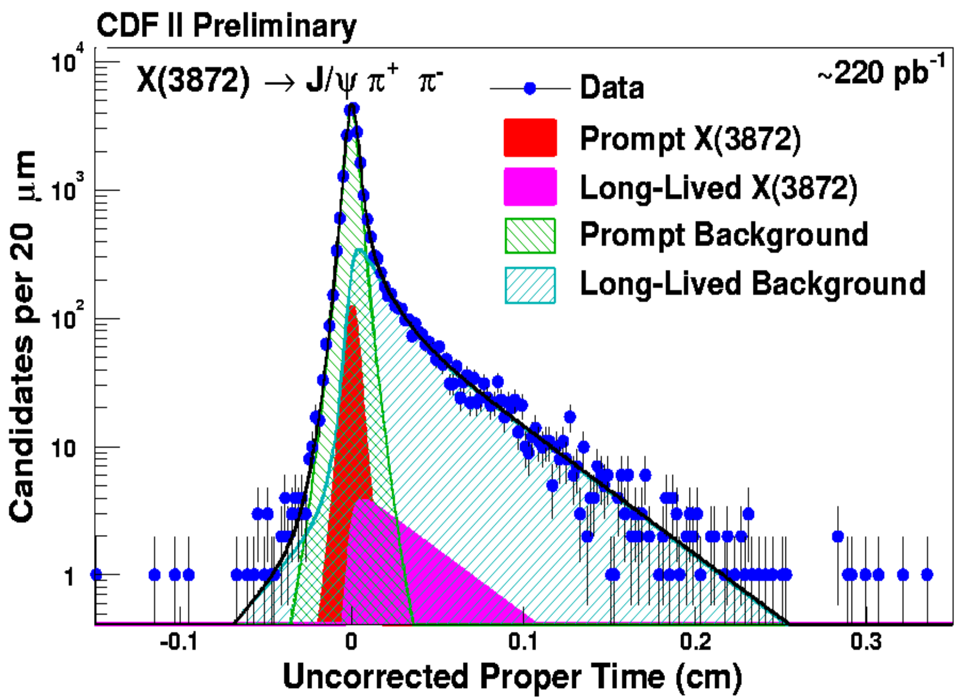
Belle: $M_X = 3872.0 \pm 0.6$ (stat) ± 0.5 (sys)

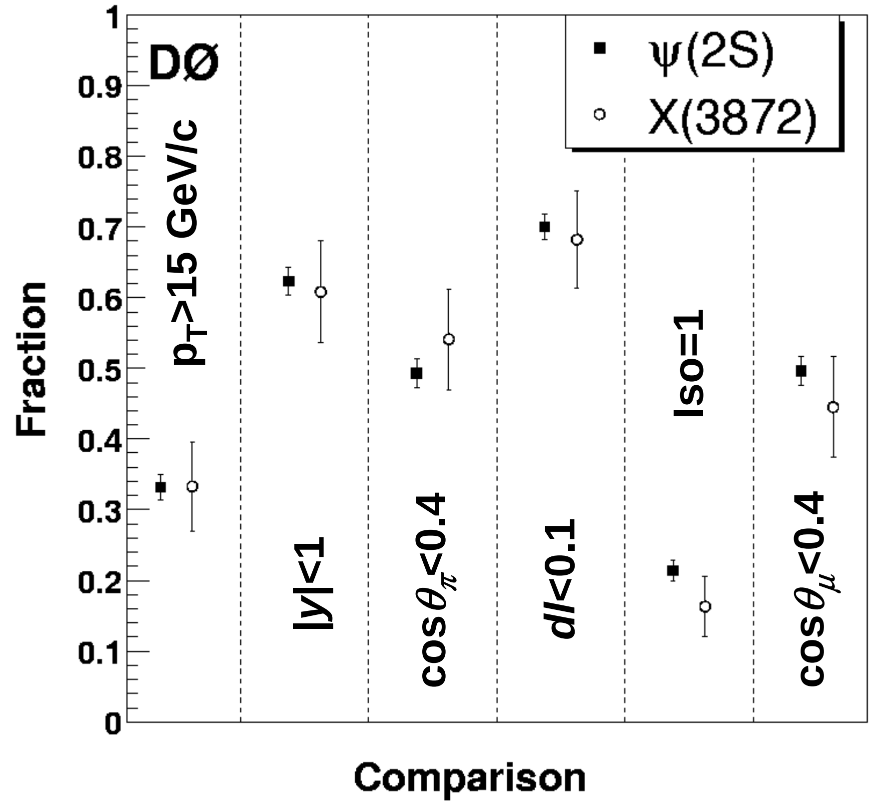
$\Delta M = 774.9 \pm 3.1$(stat) ± 3.0 (sys) MeV/c^2

$\Delta M + M(J/\psi) = 3871.8 \pm 4.3$ MeV/c^2

$X(3872)$ – $\psi(2S)$ comparison

Is the *X* charmonium, or maybe an exotic meson molecule?

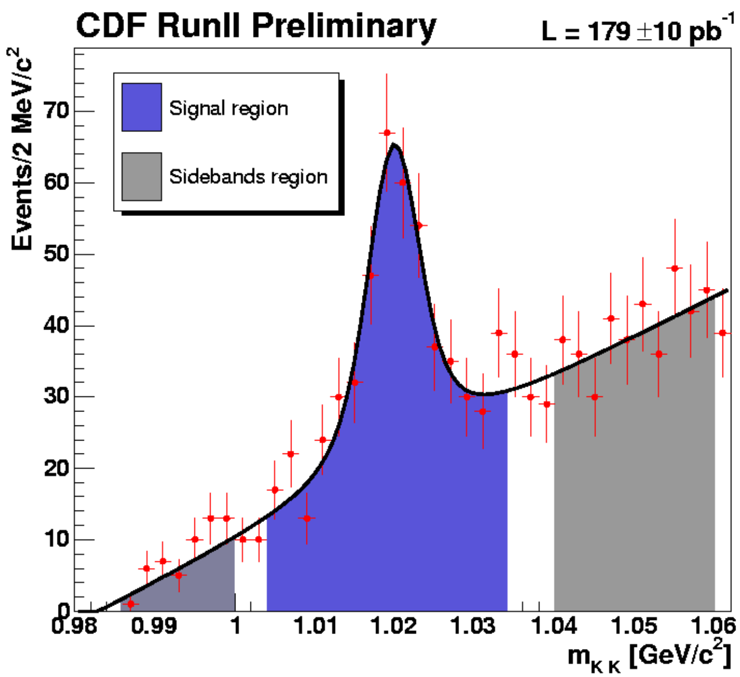


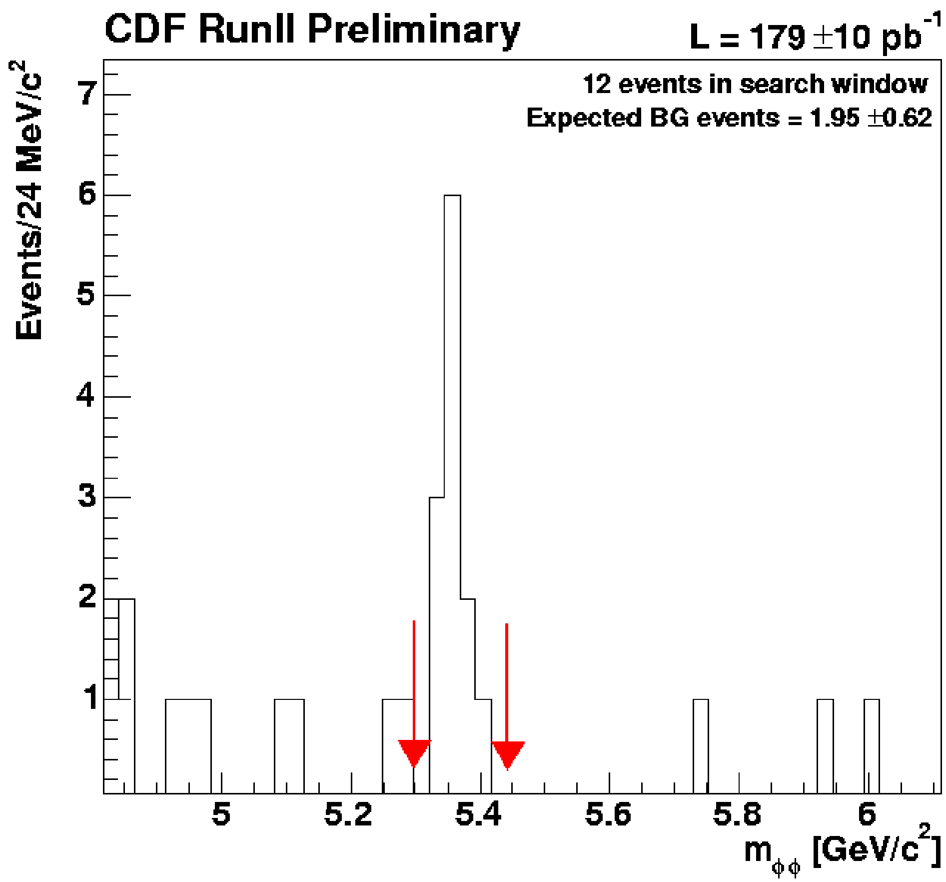


CDF Long-lifetime fraction:
$\psi(2S)$: 28.3±1.0(stat) ±0.7(syst)
$X(3872)$: 16.1±4.9(stat) ±2.0(syst)

DØ multi-parameter comparison

First Observation of $B_s \to \phi\phi$

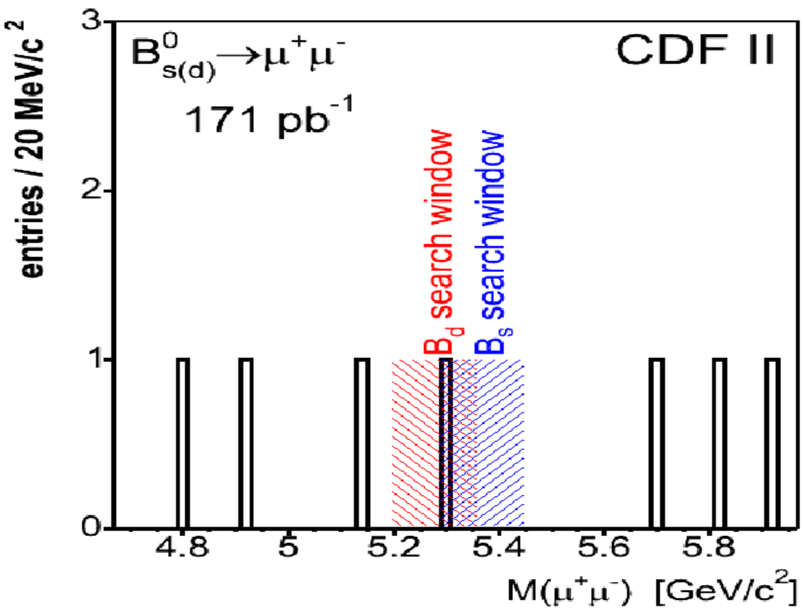


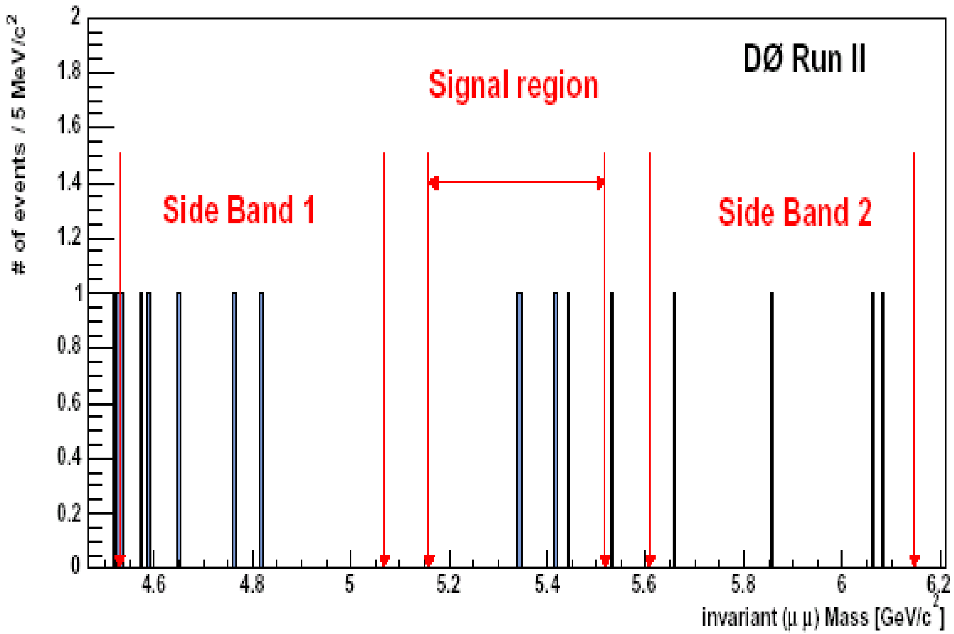


$BR(B_s \to \phi\phi) = 1.4 \pm 0.6(stat) \pm 0.2(syst) \pm 0.5(BR) \times 10^{-5}$

Search for $B^0_{(s,d)} \to \mu^+\mu^-$

SM $BR(B_s^0 \to \mu^+\mu^-) \approx (3.4 \pm 0.5) \times 10^{-9}$; $BR(B_d^0 \to \mu^+\mu^-) \approx (1.5 \pm 0.9) \times 10^{-10}$





Expected BG: 1.05 ± 0.30

Expected BG: 3.7 ± 1.1 events

$BR(B_s^0 \to \mu^+\mu^-)$: < 7.5×10^{-7} at 95% CL (CDF)

$BR(B_s^0 \to \mu^+\mu^-)$: < 4.6×10^{-7} at 95% CL (DØ)

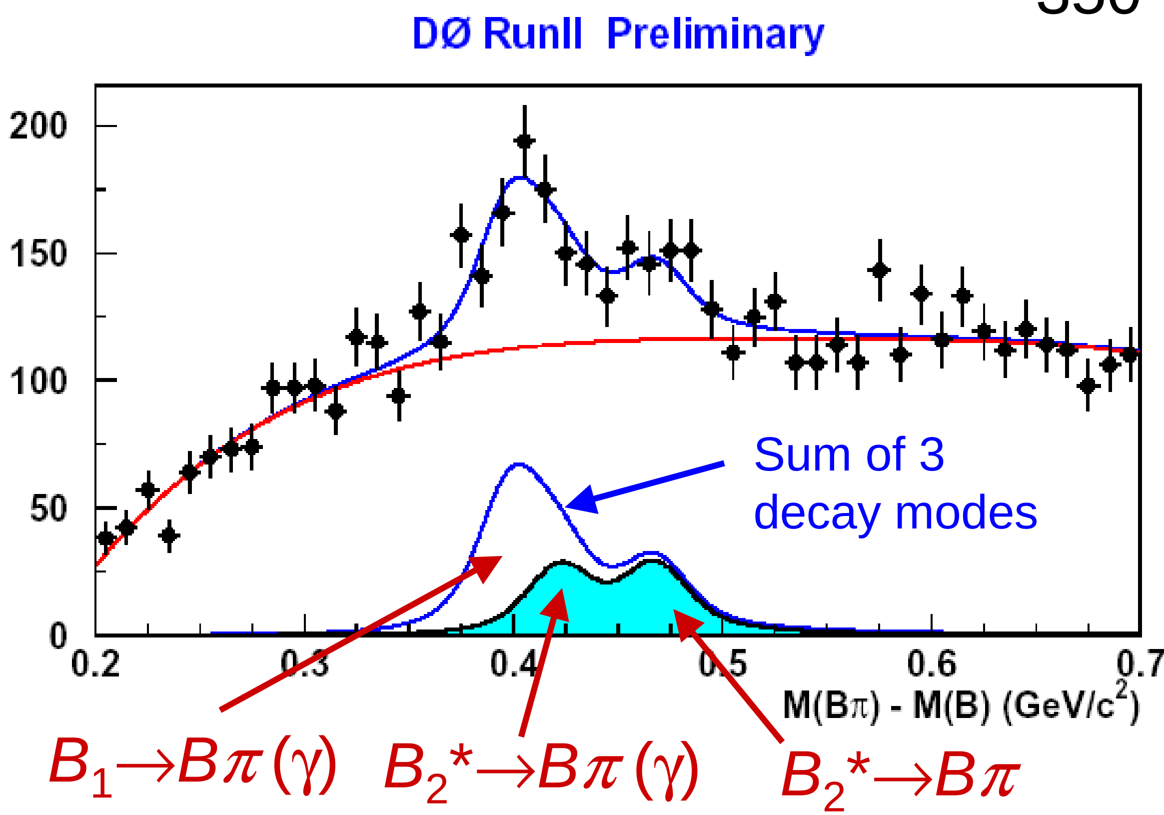
$BR(B_d^0 \to \mu^+\mu^-)$: < 1.9×10^{-7} at 95% CL

Observation of *B***

- *B* Spectroscopy:
  - B ($J^p = 0^-$)
  - B^* ($J^p = 1^-$) – decays to $B\gamma$ (100%)
    - $\Delta M = M(B^*) - M(B) = 46$ MeV/c^2
  - The *B*** consists of four separate states
    - 2 narrow states B_1 (1^+) and B_2^* (2^+), decay via D-wave;
    - 2 wide states B_0^* (0^+) and B_1' (1^+), decay via S-wave;
    - None of these individual states are well established
- Decay channels used:
  - $B_d^{**} \rightarrow B^\pm \pi^+$; $B^{**+} \rightarrow B_d \pi^+$; $B^{**} \rightarrow B^* \pi \rightarrow B\pi(\gamma)$
    - $B^\pm \rightarrow J/\psi K^\pm$; $B_d \rightarrow J/\psi K^{*0}$; $B_d \rightarrow J/\psi K^0_s$

Distinct Narrow *B*** States

350 pb^{-1}

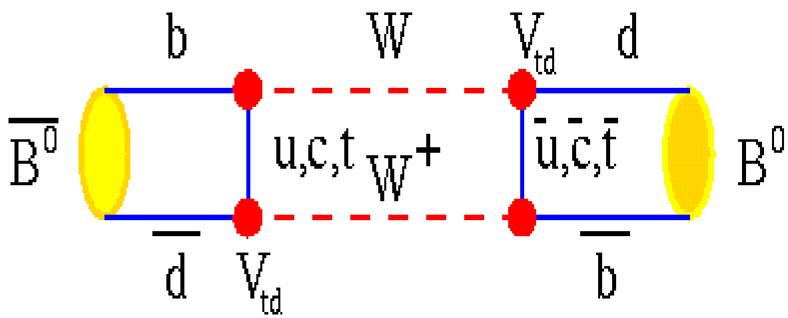


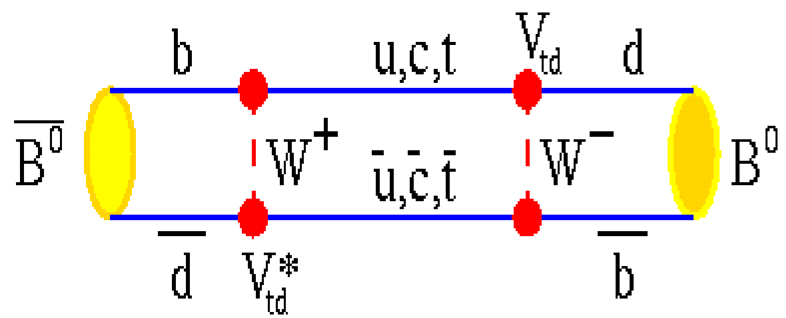
- The first direct measurement of masses and splitting between B_2^* and B_1
- $M(B^*) = M(B) + 46$ MeV (γ)

$$M(B_1) = 5724 \pm 4 \pm 7 \text{ MeV}/c^2$$

$$M(B_2^*) - M(B_1) = 23.6 \pm 7.7 \pm 3.9 \text{ MeV}/c^2$$

B_d Mixing





- In SM B_d mixing is explained by box diagrams
  - Constrains V_{td} CKM matrix element
  - Mixing frequency Δm_d has been measured with high precision at e^+e^- B factories (0.502 ± 0.007 ps^{-1})
- Δm_d measurement at Hadron Colliders
  - Confirms initial state flavor tagging for later use in B_s and Δm_s measurements

B Oscillation Variables

Opposite side

Same side

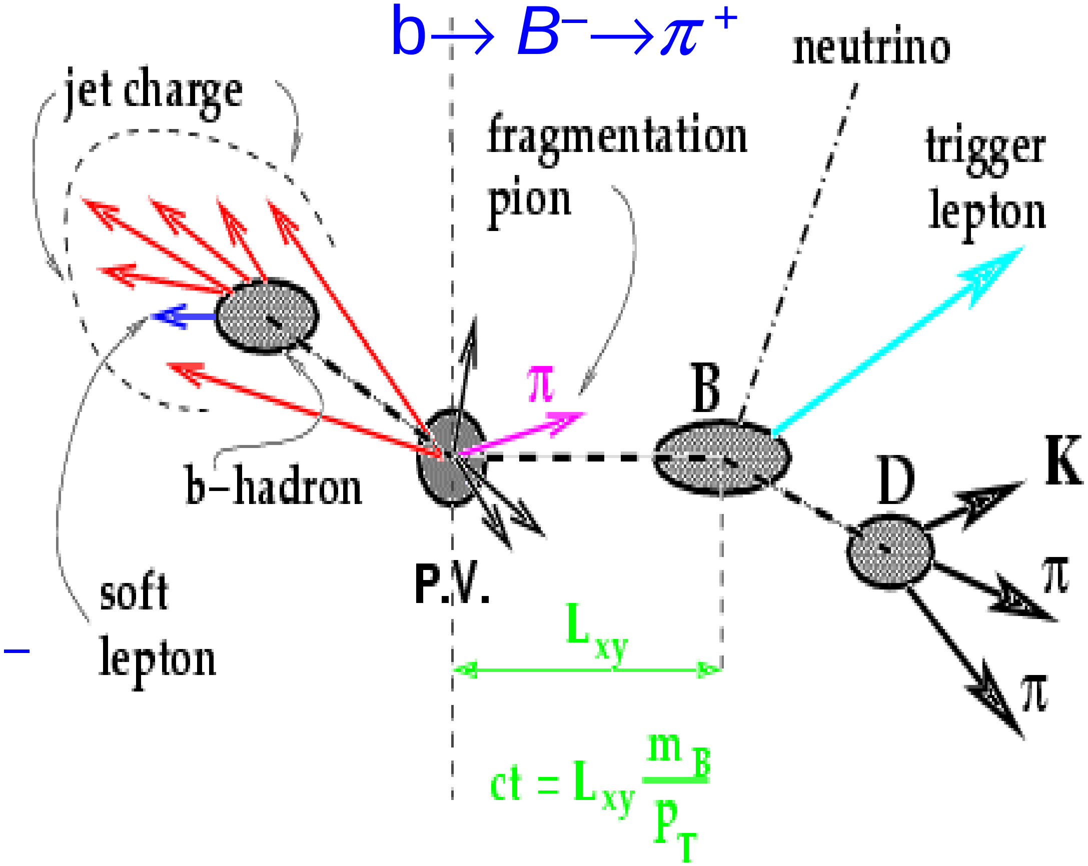
$b \to \bar{B}^0 \to \pi^-$

$b \to B^- \to \pi^+$

$b^{-1/3} \to Q<0$

$b \to K^-$ (CDF)

$b \to \ell^-$

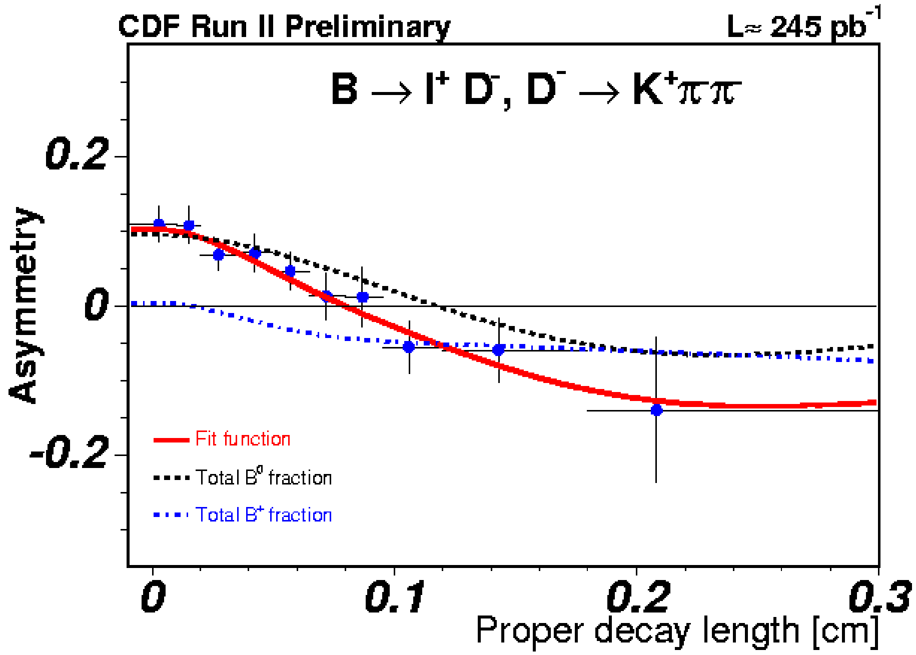


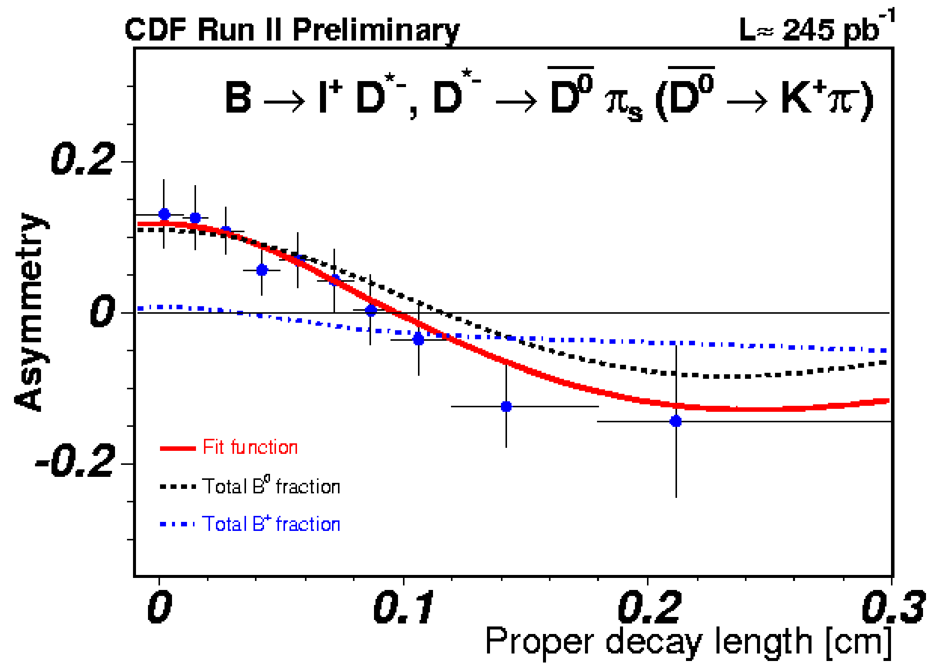
$B_s \to K^+$ (CDF)

B^0 Mixing with SS Tag

$$A = (N_{RS} - N_{WS})/(N_{RS} + N_{WS})$$

N_{RS}:N($B^0\pi^+$)
N_{WS}:N($B^0\pi^-$)

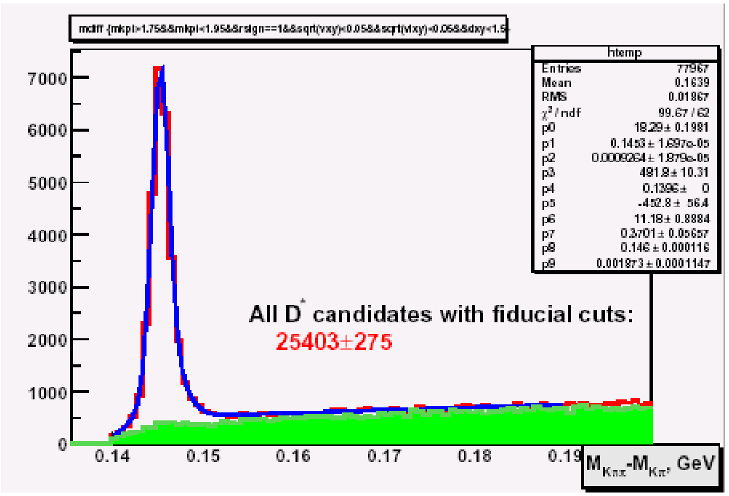


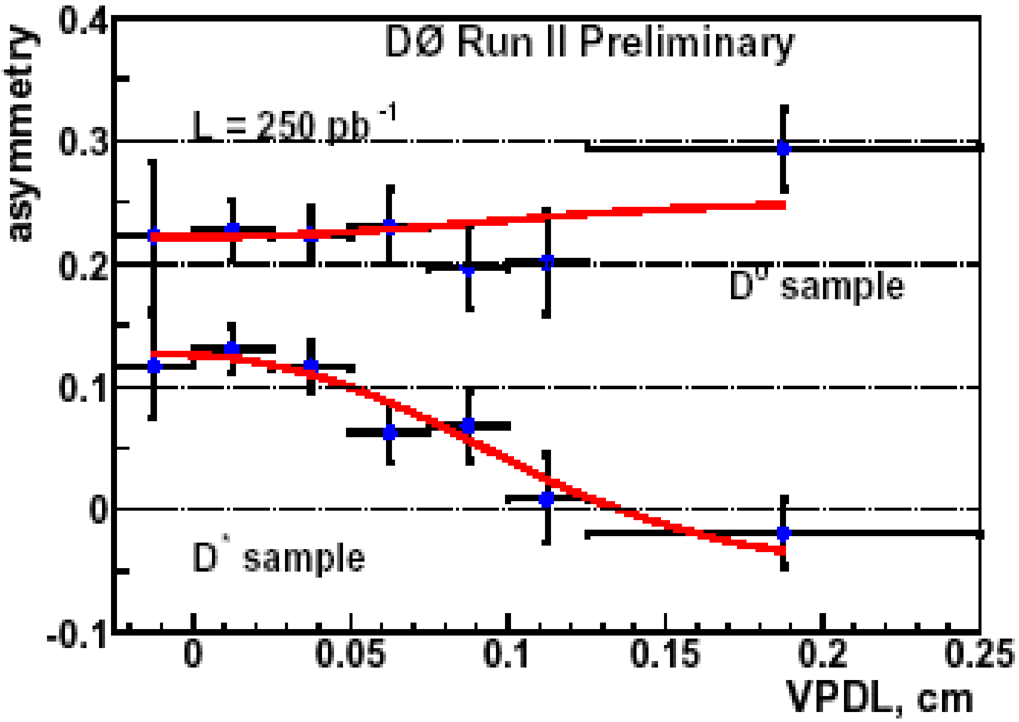


$$\Delta m_d = 0.443 \pm 0.052(\text{stat}) \pm 0.030(\text{sc}) \pm 0.012(\text{syst})\ \text{ps}^{-1}$$

B^0 Mixing with SS Tag

$B \to \mu D^* X$, $D^* \to D^0 \pi$





Visible Proper Decay Length:

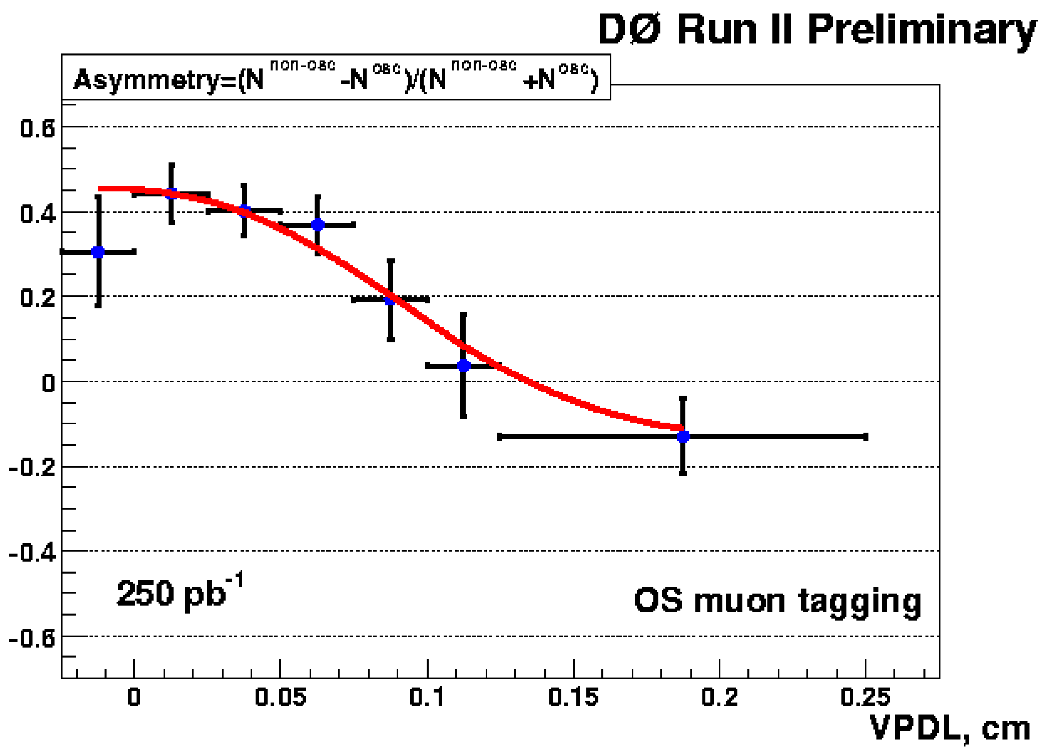
$x_M = L_{xy} M_B c / p_T^{\mu D}$

Tagging purity: 55.8 ± 0.7 ± 0.8 %

Preliminary

$\Delta m_d = 0.488 \pm 0.066(\text{stat}) \pm 0.044(\text{syst})\ \text{ps}^{-1}$

B^0 Mixing with OS μ Tag



Preliminary

Decay Mode:

- $B \to \mu D^* X$, $D^* \to D^0 \pi$

Tagging:

- muon $p_T > 2.5$ GeV/c
- $\cos \Delta\phi(\mu,B) < 0.5$
- Tagging efficiency: 4.8 ± 0.2 %
- Tagging purity: 73.0 ± 2.1 %

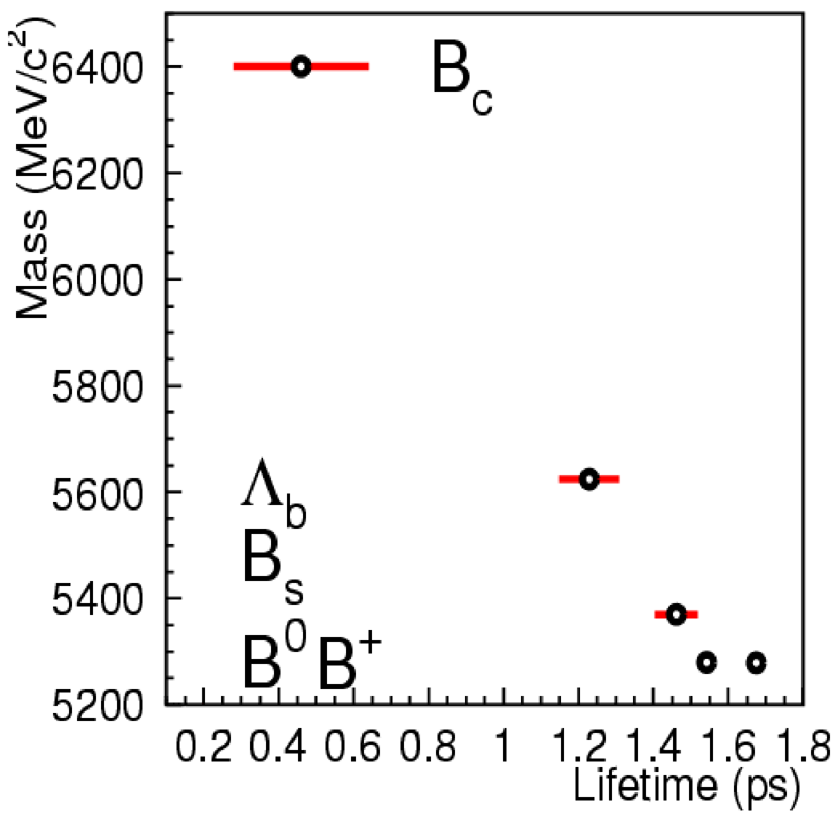
•Fit procedure

- Binned χ^2 fit

$\Delta m_d = 0.506 \pm 0.055(\text{stat}) \pm 0.049(\text{syst})\ \text{ps}^{-1}$

Combined result using three tagging methods will be released soon

B Hadron Lifetimes

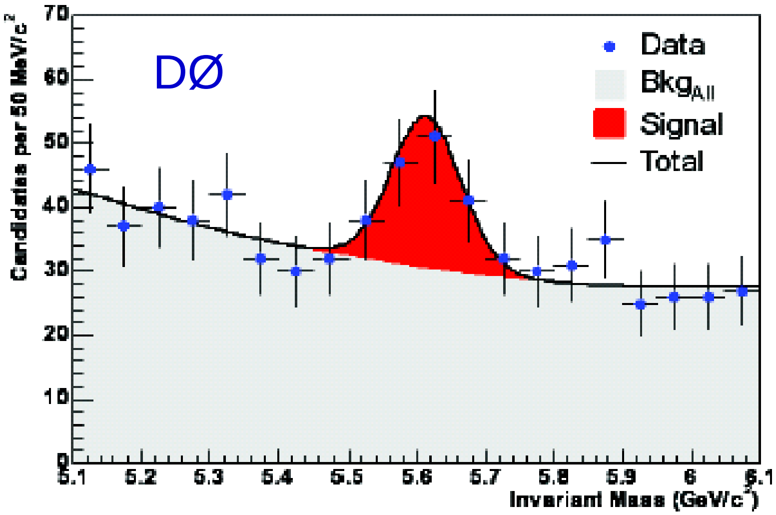


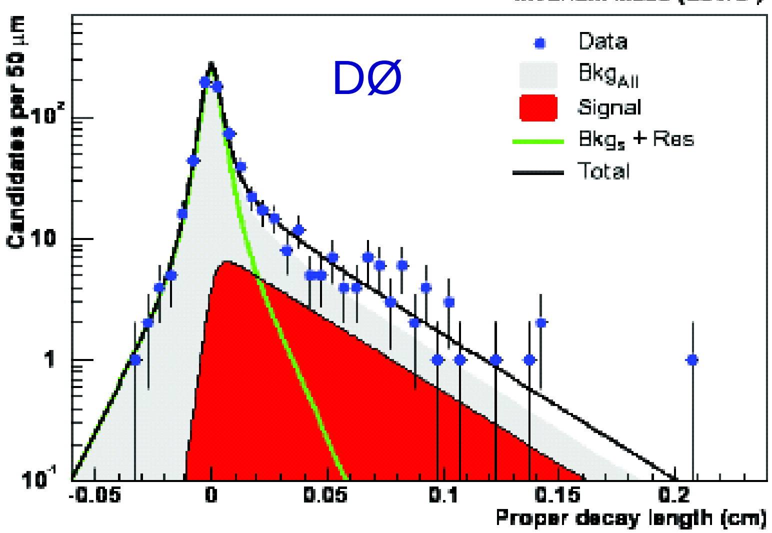
- **Naive quark spectator model**: a 1 → 3 decay process common to all *B* hadrons.
- (NLO) QCD → **Heavy Quark Expansion** predicts deviations in rough agreement with data
- Experimental and theoretical uncertainties are comparable
- Lifetime differences probe the HQE to **3rd** order in Λ_{QCD} **/ m_b**
- **Goal: measure the ratios accurately**

B Hadron Lifetime Ratios

Λ_b Lifetime

DØ Preliminary





New Measurement from DØ

$\Lambda_b \rightarrow J/\psi\, \Lambda^0$

$\tau(\Lambda_b) = 1.221\ ^{+0.217}_{-0.179} \pm 0.043$ ps

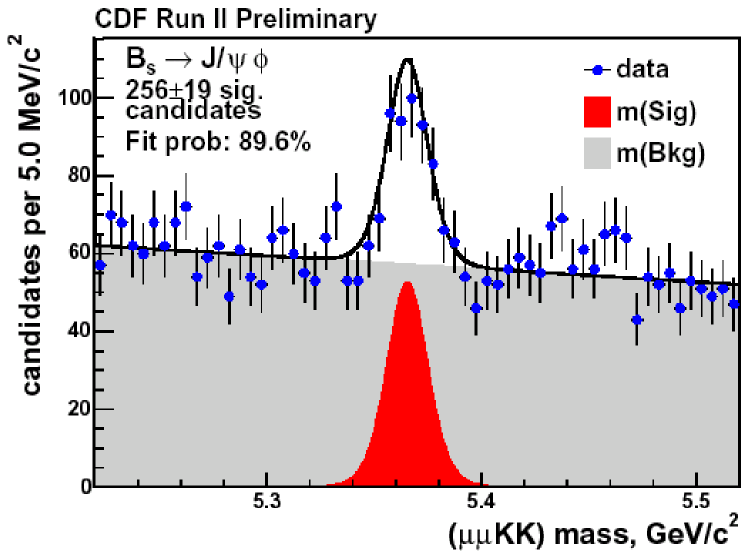
$\tau(\Lambda_b)/\tau(B_d^0) = 0.874\ ^{+0.169}_{-0.142} \pm 0.028$

CDF Preliminary from 2003:

$\tau(\Lambda_b) = 1.25 \pm 0.26 \pm 0.10$ ps

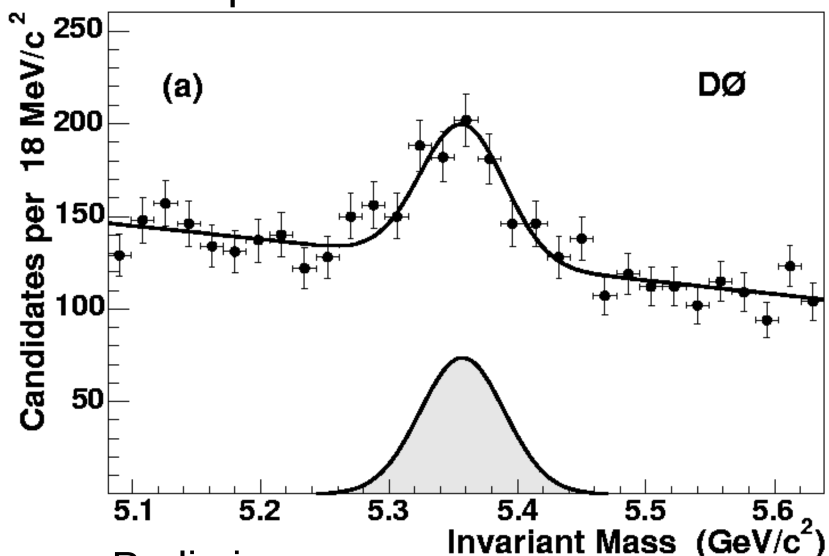
B_s Lifetime using $B_s \to J/\psi\, \phi$

CDF



DØ

250 pb^{-1}



Preliminary

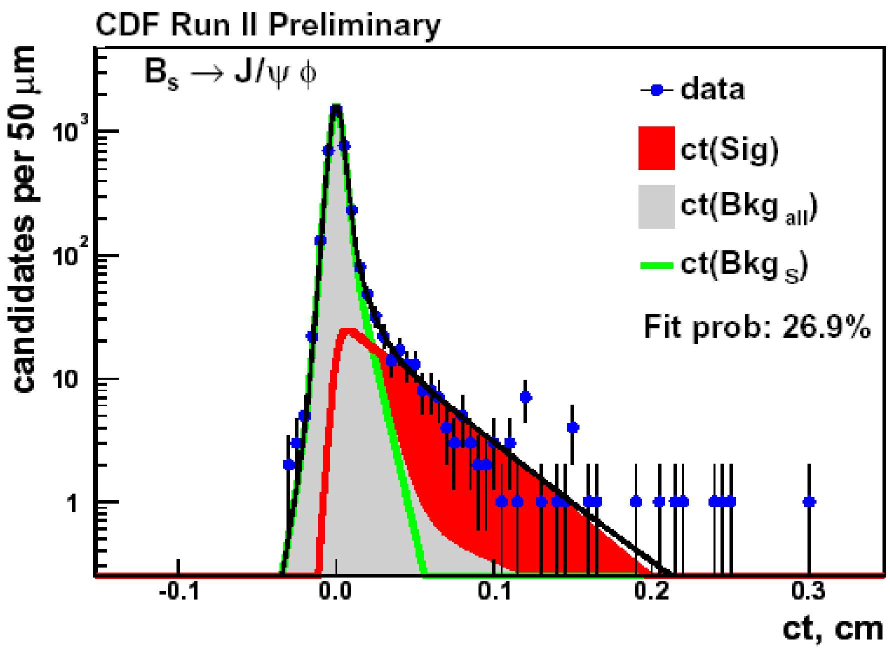
Improvements since 2003:

- Selection minimizes ***stat ⊕ syst***
- 12 parameter maximum likelihood fit
- 240 pb^{-1}

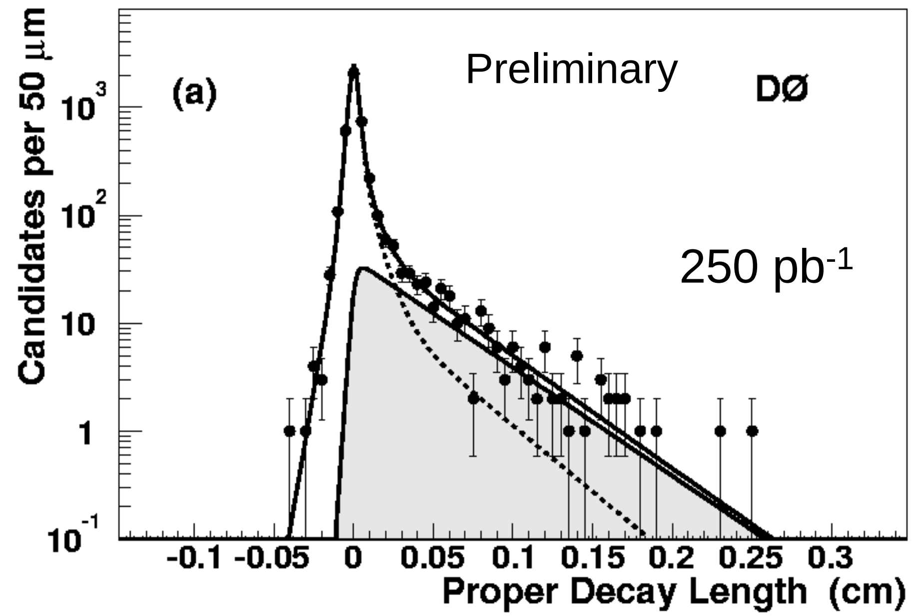
DØ analysis is similar to this CDF "improved" analysis

B_s Lifetime using $B_s \to J/\psi\,\phi$

CDF



DØ



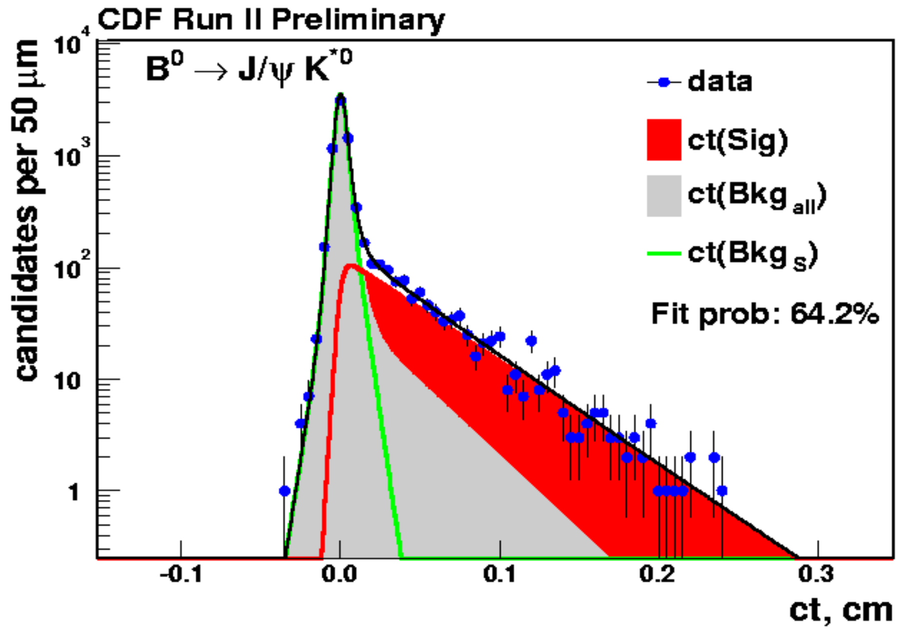
$\tau(B_s) = 1.369 \pm 0.100\,^{+0.008}_{-0.010}$ ps

$\tau(B_s) = 1.444\,^{+0.098}_{-0.090} \pm 0.020$ ps

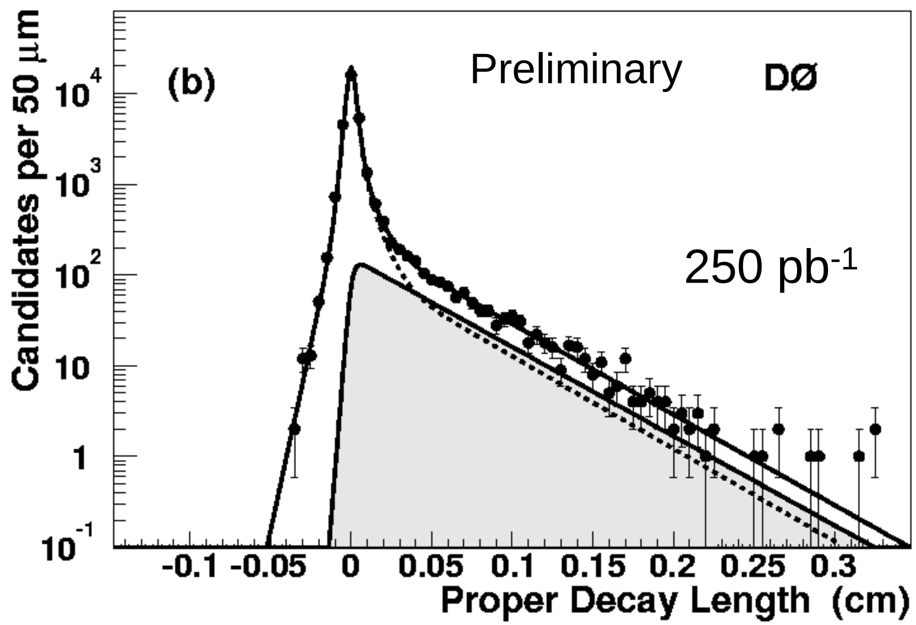
Uses one exponential decay in the fit

B_d Lifetimes Using $B_d \to J/\psi\, K_s^{*0}$

CDF



DØ



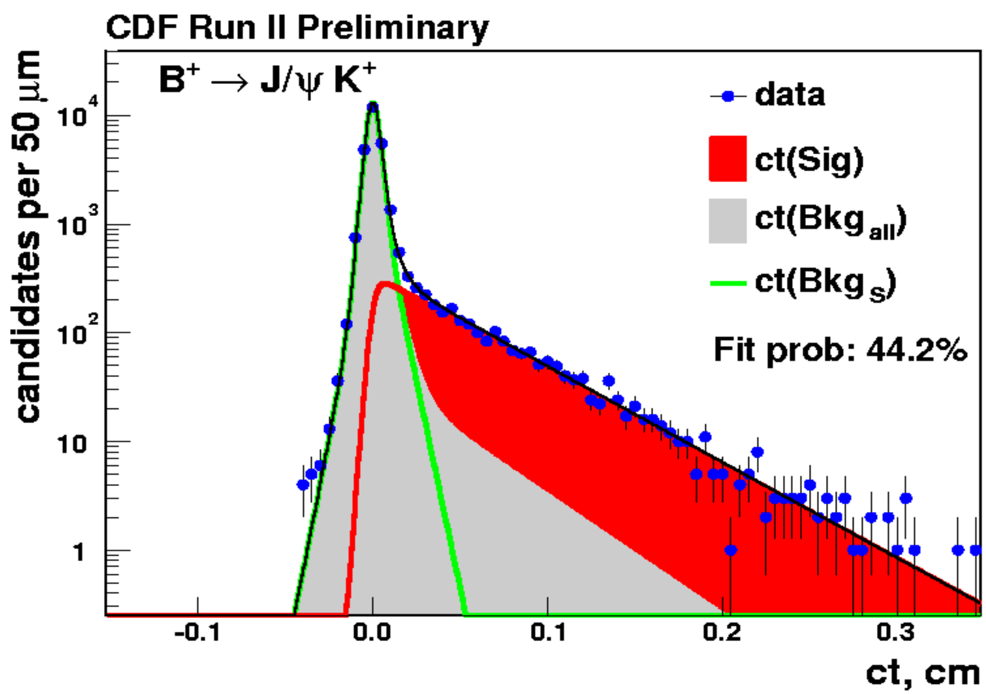
$\tau(B^0) = 1.539 \pm 0.051 \pm 0.008$ ps

$\tau(B_d^0) = 1.473^{+0.052}_{-0.050} \pm 0.023$ ps

$\tau(B_s)/\tau(B^0) = 0.890 \pm 0.072$

$\tau(B_s)/\tau(B^0) = 0.980^{+0.075}_{-0.070} \pm 0.003$

B^+ Lifetime Using $B \to J/\psi K^+$



$\tau(B^+)$ = 1.662±0.033±0.008 ps

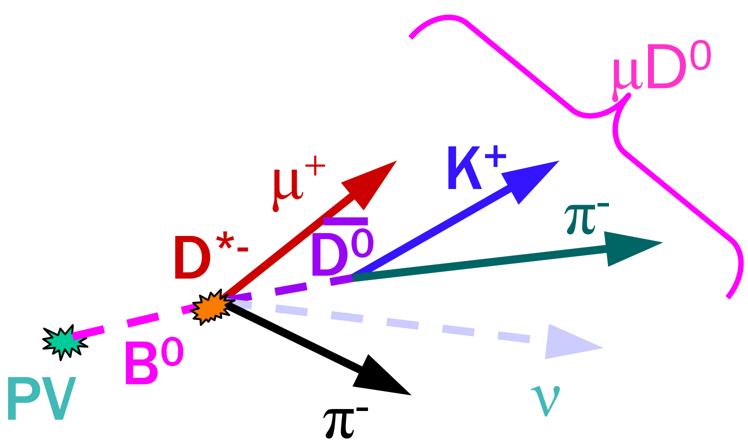
$\tau(B^+)/\tau(B^0)$ = 1.080±0.042

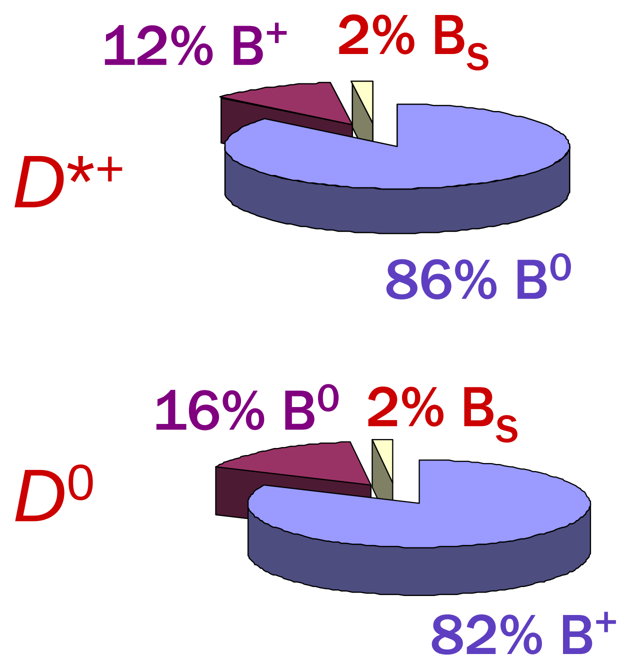
Most systematic uncertainties cancel in the ratio

Lifetime Ratio $\tau(B^+)/\tau(B^0)$

Novel Analysis Technique using $B \rightarrow \mu D^{c(*)} X$

- Directly measure ratio instead of individual lifetimes
- Split $D^0 \rightarrow K\pi$ sample:
  - D^{*+} (with slow π^+) ← mainly from B^0
  - D^0 ← mainly from B^+

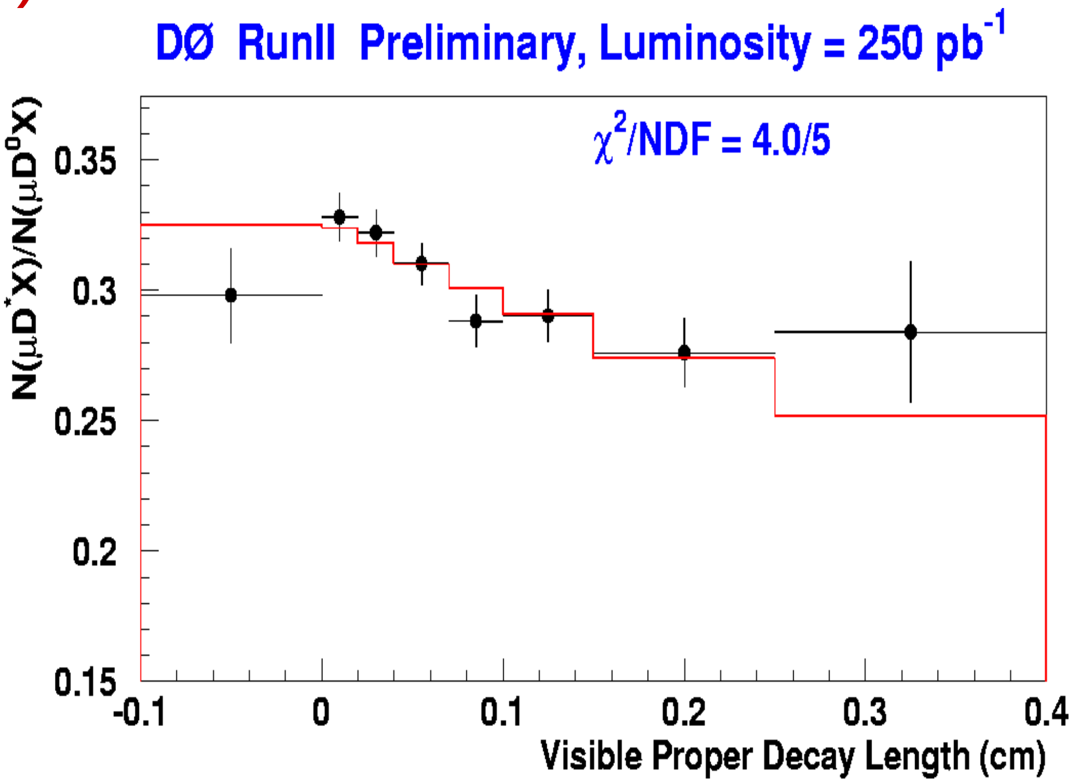




Lifetime Ratio $\tau(B^+)/\tau(B^0)$

- Measure $N(\mu D^{*+})/N(\mu D^0)$ in bins of VPDL
- In both cases fit D^0 signal to extract N
- Use slow pion only to distinguish B^0 from B^+

  (not in vertexing, K-factors etc., to avoid lifetime bias)



$$\tau(B^+)/\tau(B^0) = 1.093 \pm 0.021(\text{stat}) \pm 0.022(\text{syst})$$

B Decay Angular Amplitudes

- Uses $B_s \rightarrow J/\psi\,\phi$; Uses $B_d \rightarrow J/\psi\,K^{*0}$
- Allows measurement of many parameters including polarization amplitudes and $\Delta\Gamma_s = 1/\tau_L - 1/\tau_H$

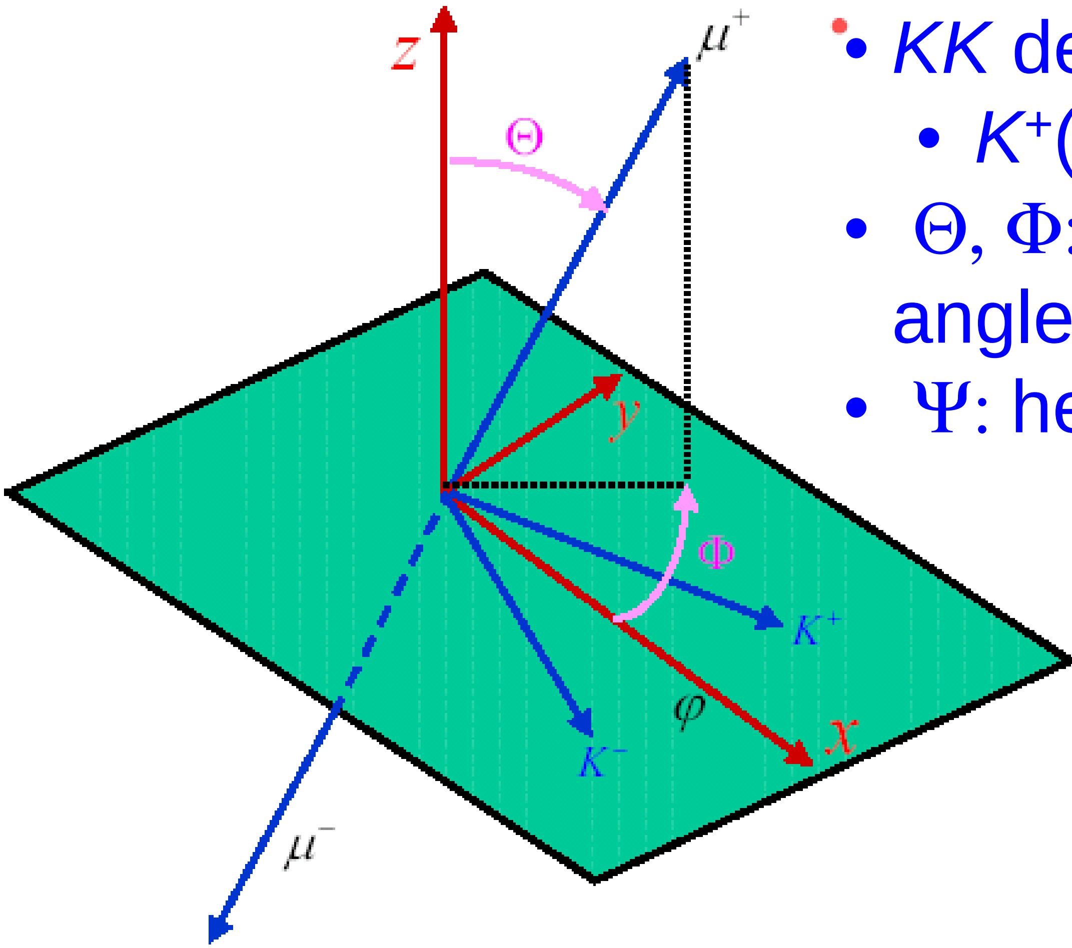
$$\left|B_s^H\right\rangle = p\left|B_s\right\rangle + q\left|\overline{B}_s\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_s\right\rangle + \left|\overline{B}_s\right\rangle\right) \quad \text{CP odd}$$

$$\left|B_s^L\right\rangle = p\left|B_s\right\rangle - q\left|\overline{B}_s\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_s\right\rangle - \left|\overline{B}_s\right\rangle\right) \quad \text{CP even}$$

$$\left|B_s\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_s^H\right\rangle + \left|B_s^L\right\rangle\right)$$

$$\left|\overline{B}_s\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_s^H\right\rangle - \left|B_s^L\right\rangle\right)$$

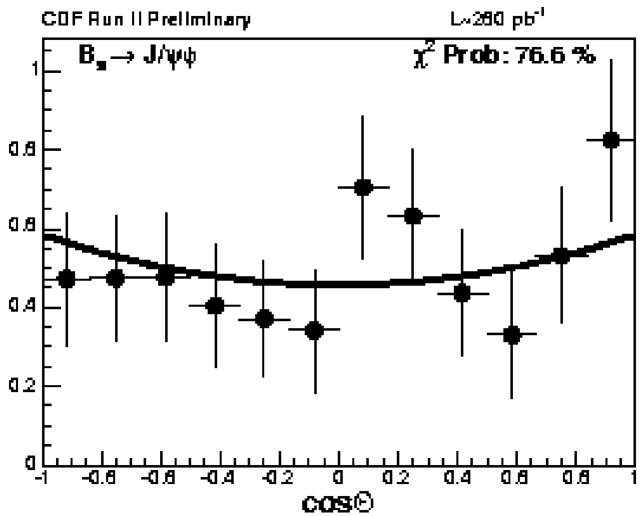
Transversity Angles

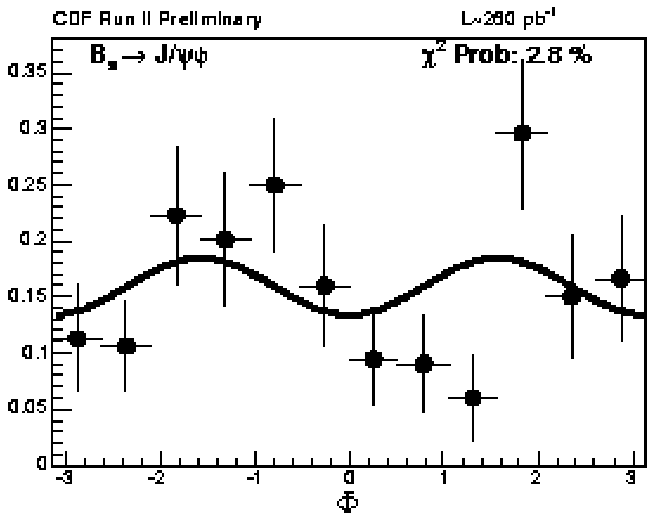


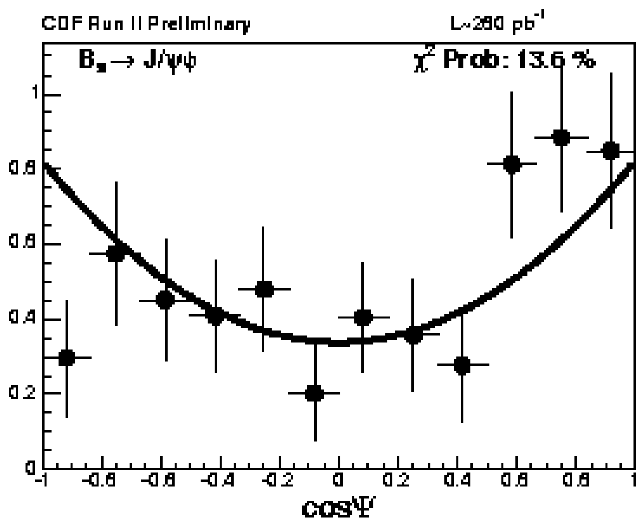
- The J/ψ rest frame
- KK defines (x,y) plane
  - $K^+(K)$ defines $+y$ direction
- Θ, Φ: polar & azimuthal angles of μ^+
- Ψ: helicity angle of $\phi(K^*)$

Extract polarization amplitudes:
A_0: Longitudinal
$A_{||}$, $A_{\perp}$: Transverse

Angular Projections and fit for B_s







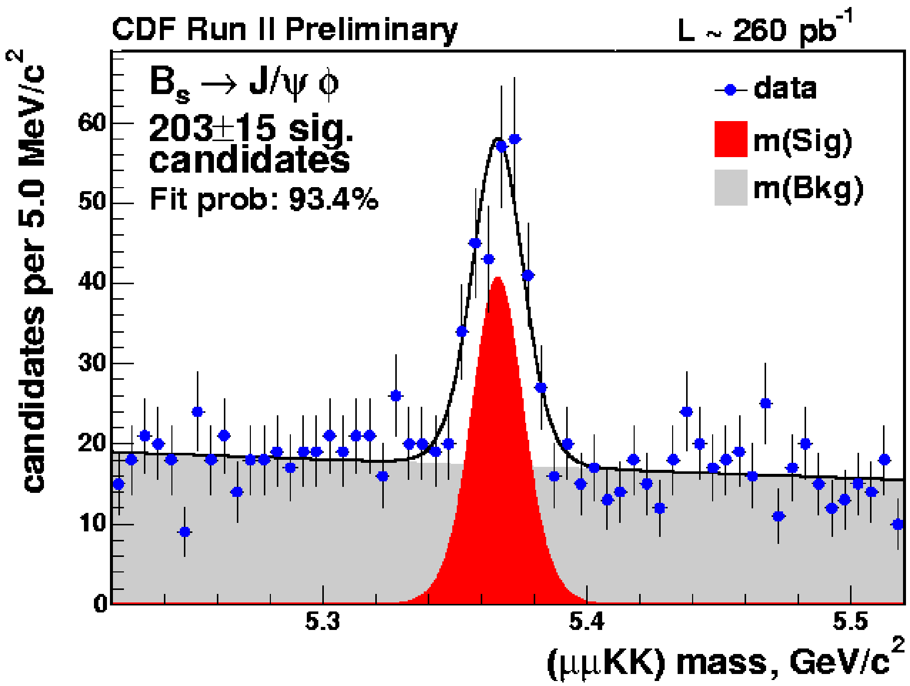
Decay Angular Distribution:

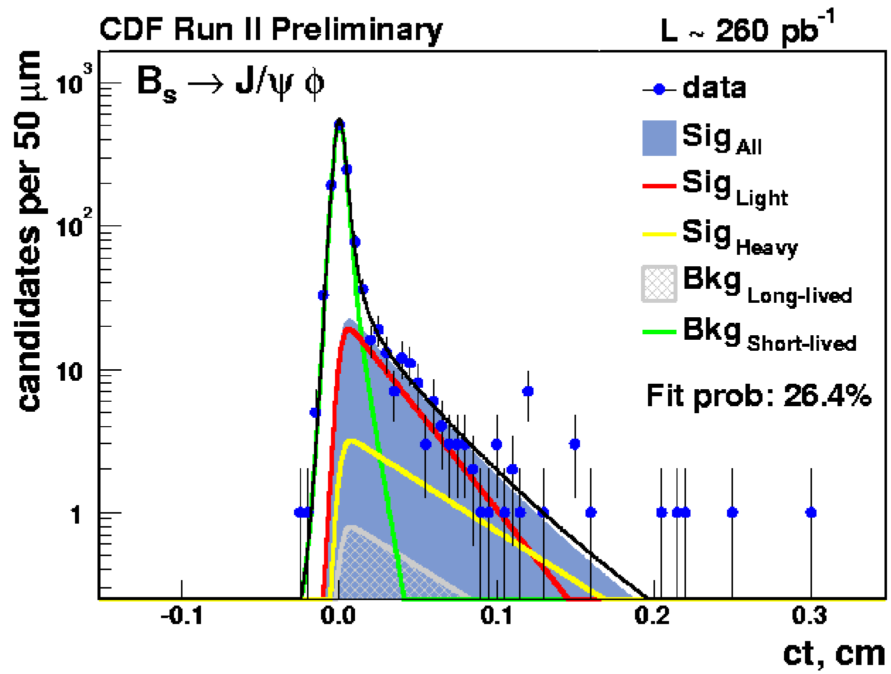
$$\frac{d^4P}{d\vec{\rho}\, dt} = \sum_{i=1}^{6} A_i \cdot g_i(t) \cdot f_i(\vec{\rho})$$

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

B_s Mass and Lifetime Projections

Unconstrained fit





$$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02 \text{ ps}$$

$$\tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03 \text{ ps}$$

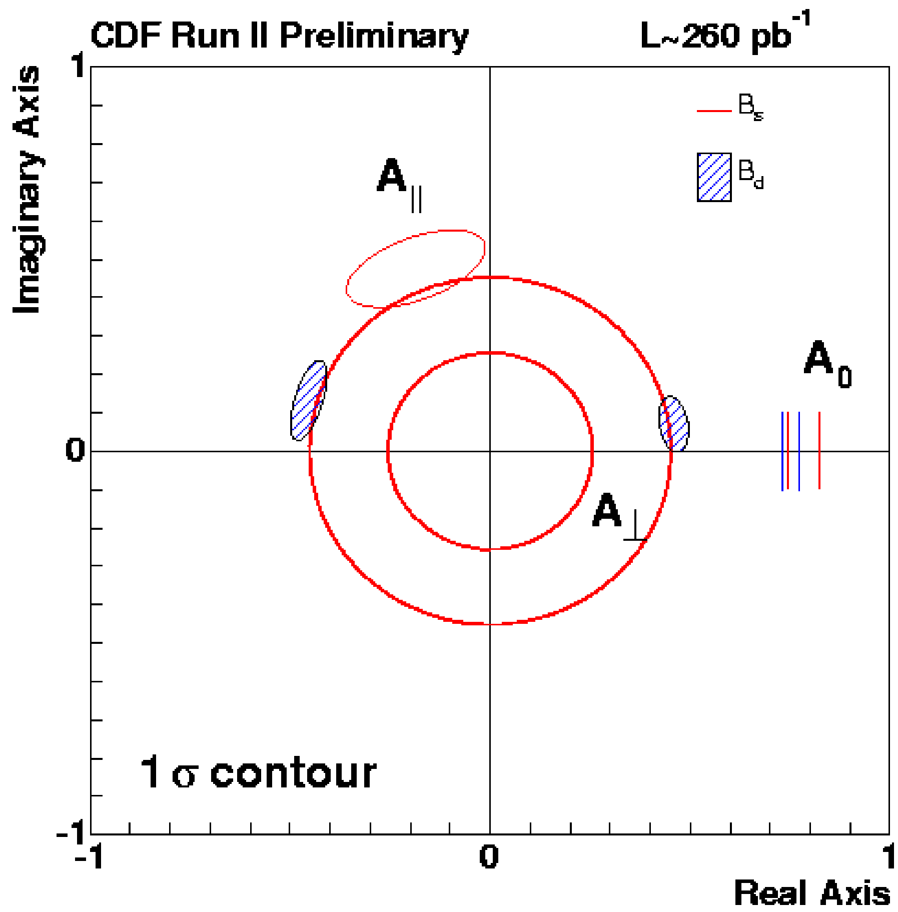
$$\Delta\Gamma = 0.47^{+0.19}_{-0.24} \pm 0.01 \text{ ps}^{-1}$$

$$\frac{\Delta\Gamma}{\Gamma} = 0.65^{+0.25}_{-0.33} \pm 0.01$$

Using SM and constrained fit:

$$\Delta m_s = 125^{+65}_{-55} \text{ ps}^{-1}$$

B_s and B_d Amplitudes



For B_d^0

$A_0 = 0.750 \pm 0.017 \pm 0.012$

$A_{||} = (0.473 \pm 0.034 \pm 0.006) \times e^{i(2.86 \pm 0.22 \pm 0.04)}$

$|A_\perp| = (0.482 \pm 0.104 \pm 0.014) \times e^{i(0.15 \pm 0.15 \pm 0.04)}$

For B_s^0

$A_0 = 0.784 \pm 0.039 \pm 0.007$

$A_{||} = (0.510 \pm 0.082 \pm 0.013) \times e^{i(1.94 \pm 0.36 \pm 0.03)}$

$|A_\perp| = 0.354 \pm 0.098 \pm 0.003$

DØ results coming soon

Conclusions

- DØ and CDF are measuring many properties of *B* hadrons that nicely complement those measured at "*B* factories"
- We expect 500 pb^{-1} by the end of the year
- More exciting results are expected even in the next few weeks