# B Physics at the Tevatron II
## *Lifetimes and $\Delta\Gamma$*

*Ronald Lipton, Fermilab*
*For the CDF and D0 collaborations*

New results for Moriond 2005

- Lifetimes in semileptonic decays
  - $B^0, B^+$ (CDF)
  - $B_s$ (D0)
- Lifetimes in Hadronic decays (CDF)
- $\Delta\Gamma$ $B_s$ (D0)

# Lifetime Measurements

- Collider experiments are beginning to provide precision measurements of $B_s$, $\Lambda_b$, $B_c$ , $B^0$, $B^-$ lifetimes
- Verify HQET predictions
- Input to other measurements
- Try to measure ratios to minimize systematics
- Pre-Moriond results:

D0

$$B_s \to J/\psi\phi \qquad \tau_{B_s} = 1.444^{+0.098}_{-0.090} \pm 0.023\, ps$$

$$\tau_{B_s}/\tau_{B^0} = 0.980^{+0.076}_{-0.071} \pm 0.003$$

$$\Lambda_B \to J/\psi\Lambda \qquad \tau_{\Lambda_B} = 1.22^{+0.22}_{-0.18} \pm 0.04\, ps$$

$$\tau_{\Lambda_B}/\tau_{B^0} = 0.87^{+0.17}_{-0.14} \pm 0.03$$

$$B_c \to J/\psi\mu \qquad \tau_{B_c} = 0.448^{0.123}_{-0.06} \pm 0.121$$

$$\tau\left(B^+/B^0\right) = 1.080 \pm 0.016 \pm 0.014$$

CDF

$$B_s \to J/\psi\phi \qquad \tau_{B_s} = 1.369 \pm 0.100^{+0.008}_{-0.010}\, ps$$

$$B^0 \to J/\psi K^{*0} \qquad \tau_{B^0} = 1.539 \pm 0.051 \pm 0.008\, ps$$

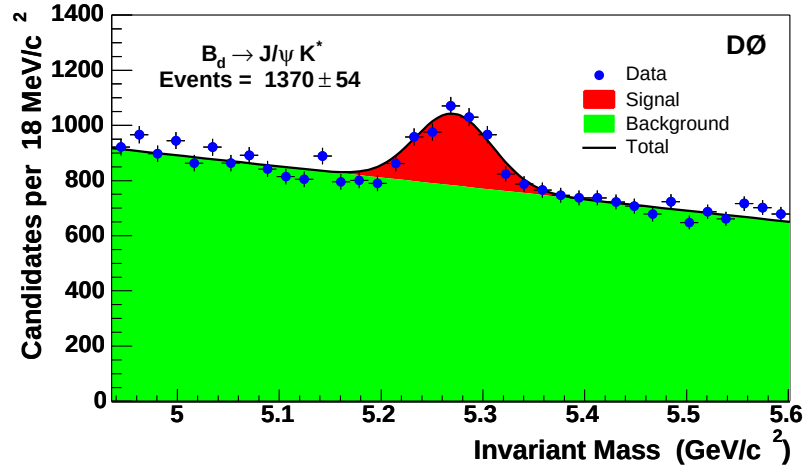
$$B^+ \to J/\psi K^+ \qquad \tau_{B^+} = 1.662 \pm 0.033 \pm 0.008\, ps$$

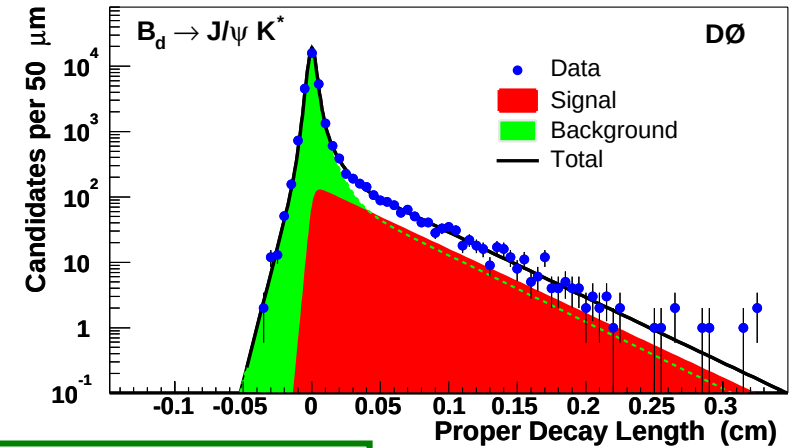
$$\Lambda_B \to J/\psi\Lambda \qquad \tau_{\Lambda_B} = 1.25 \pm 0.26 \pm 0.10\, ps$$

$$\tau\left(B^+/B^0\right) = 1.119 \pm 0.046 \pm 0.014$$

# Lifetime Fits

- Unbinned maximum likelihood components
  - Signal lifetime
  - Background lifetimes
  - Background fractions
  - B mass peak (signal fraction)
  - Momentum resolution, for each decay mode and type j, $K_j$
  - $c\tau$ resolution scale factor, s
  - Typically ~15 parameters
- Likelihood functions:




$$F_{B_j} = \frac{K_j}{c\tau}\int D(K_j)\,dK_j \exp\left(-\frac{K_j L_{xy}(m_B/P_\perp)}{c\tau}\right) \otimes Resolutions$$

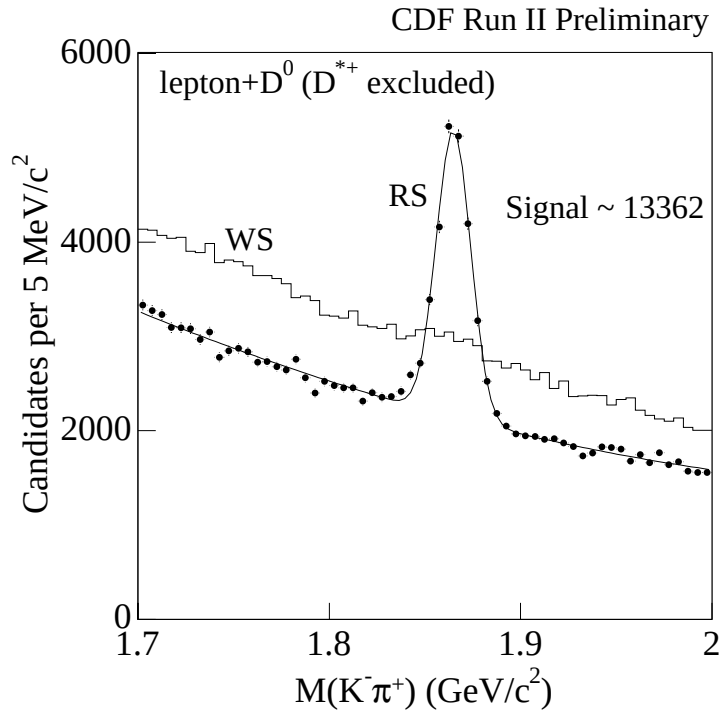
$$F_{bg} = Gaussians + \sum \frac{f_i}{\lambda_i}\exp(-\lambda_k/\lambda_i) \otimes Resolutions$$

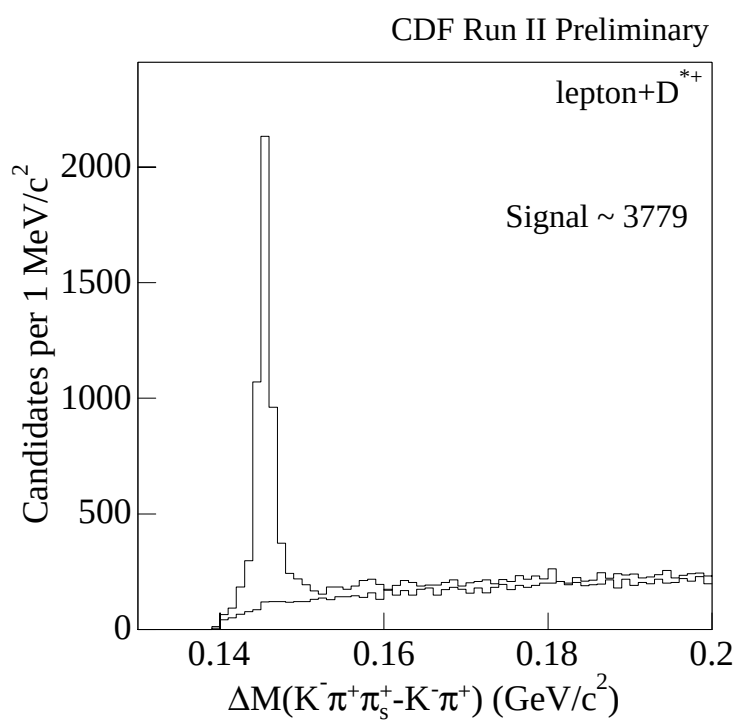
$$L = f_{signal}F_B + (1 - f_s)F_{bg}$$

# Semileptonic $B^0$, $B^-$

- Uses electron and muon triggers ~260 $pb^{-1}$
- No trigger lifetime bias
- Different semileptonic branching ratios of $B^0$, $B^-$ into $D, D^{*-}$ allows extraction of the two lifetimes and their ratios

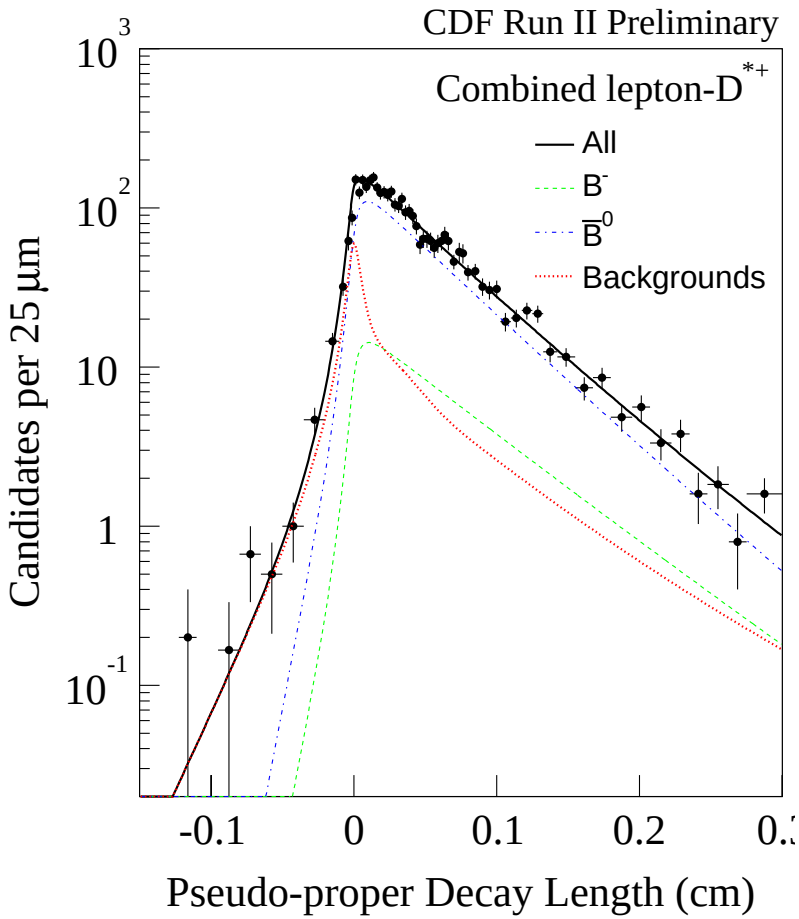
$$\tau(B^-) = 1.653 \pm 0.029^{+0.033}_{-0.031}\, ps$$
$$\tau(B^0) = 1.473 \pm 0.036 \pm 0.054\, ps$$
$$\tau(B^-)/\tau(B^0) = 1.123 \pm 0.040^{+0.041}_{-0.039}$$



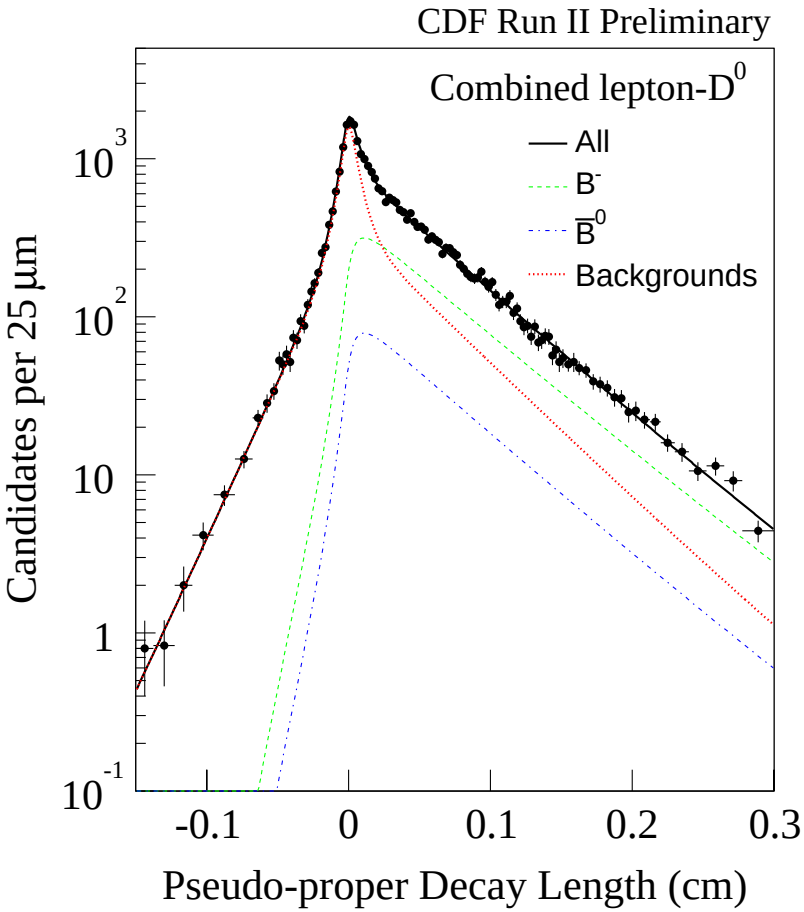



# CDF Semleptonic Lifetimes

Mostly $B^0$

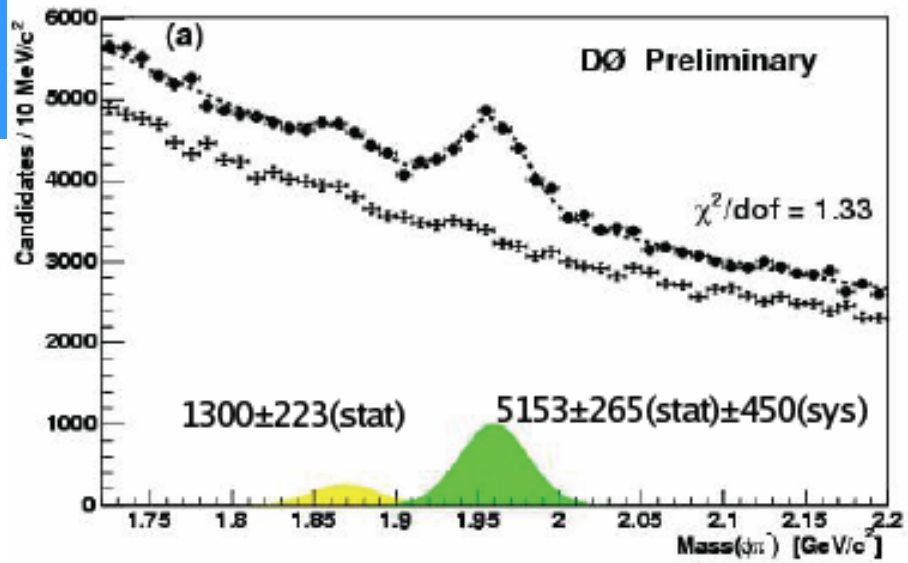


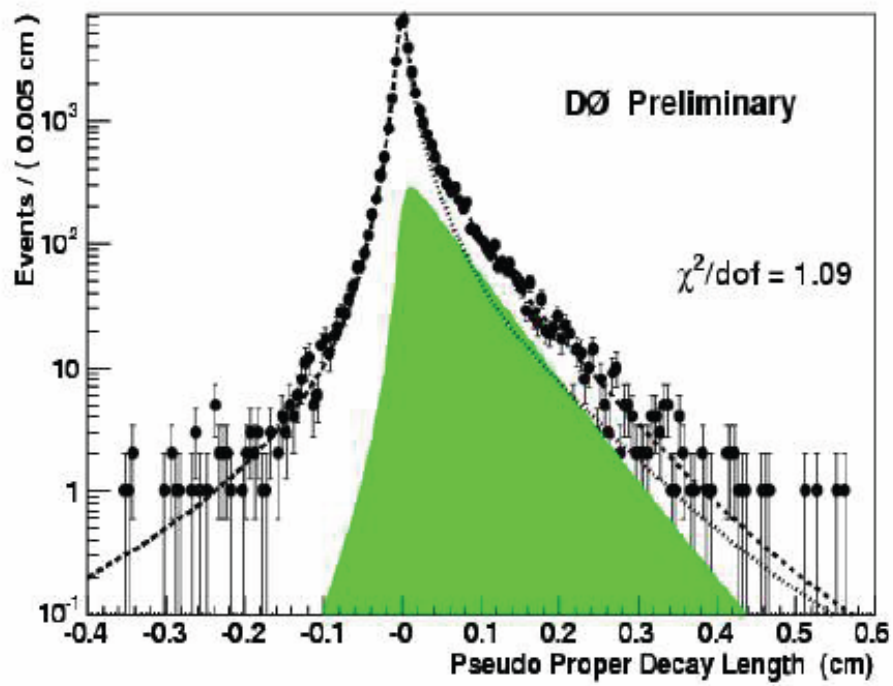

Mostly $B^-$



# Semileptonic $B_s$

- $B_s \rightarrow D_s \mu \nu X$
- Large data sample from muon triggers ~400 $pb^{-1}$
- Take *K* distribution from several semileptonic modes, $B^0$,$B^-$
- Include charm backgrounds in the fit (wide tails)




Sample Composition

| | |
|---|---|
| 25.4% | $B_s^0 \rightarrow D_s^- \mu^+ \nu X$ |
| 67.7% | $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu X$ |
| 2.4% | $B_s^0 \rightarrow D_{s0}^{*-} \mu^+ \nu X$ |
| 4.5% | $B_s^0 \rightarrow D_{s1}^{'-} \mu^+ \nu X$ |

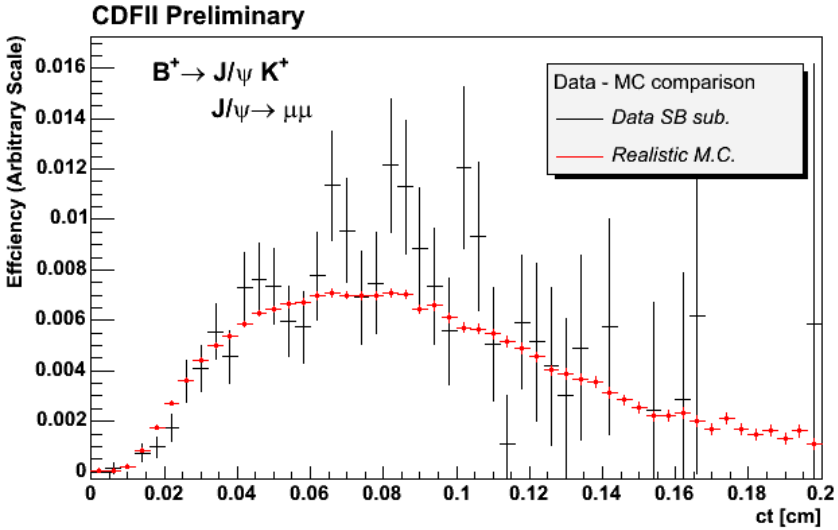
Total Br: 7.9 %

$$\tau(B_s) = 1.420 \pm 0.043 \pm 0.057$$

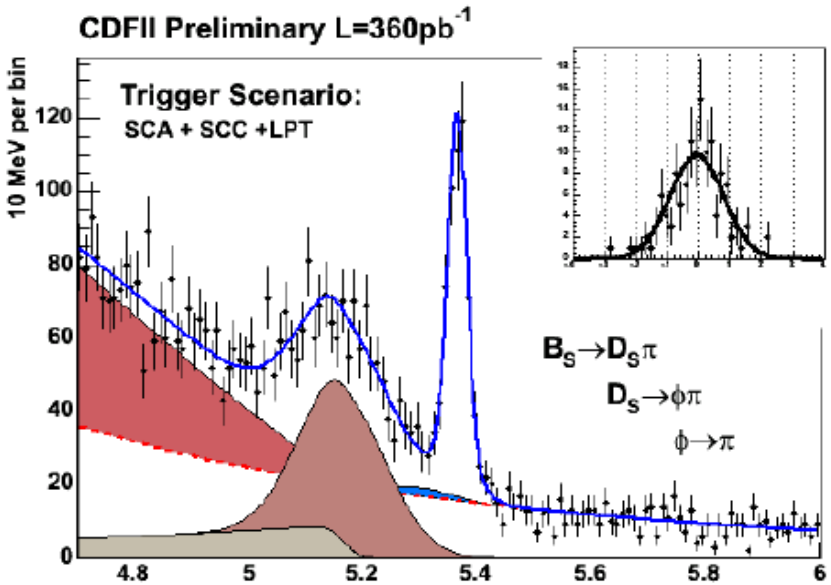
# CDF Hadronic modes

- First lifetime results to use events triggered by SVT (silicon vertex trigger)
- ~360 pb-1
- Impact parameter biases lifetime distributions but provides large samples
- Correct for trigger bias using Monte Carlo – verify with $B^-$
  - Systematics ~ 4-5 μm
- Five modes:

- ✓ $B^{\pm} \to D^0 \pi^{\pm}$ $(D^0 \to K^- \pi^+)$
- ✓ $B^0 \to D^{\mp} \pi^{\pm}$ $(D^- \to K^+ \pi^- \pi^-)$
- ✓ $B^0 \to D^{\mp} 3\pi^{\pm}$ $(D^- \to K^+ \pi^- \pi^-)$
- ✓ $B_S \to D_S^{\mp} \pi^{\pm}$ $(D_S^- \to \phi \pi^-)$ $(\phi \to K^+ K^-)$
- ✓ $B_S \to D_S^{\mp} 3\pi^{\pm}$ $(D_S^- \to \phi \pi^-)$ $(\phi \to K^+ K^-)$




$B_S \to D_S^{\mp} \pi^{\pm}$

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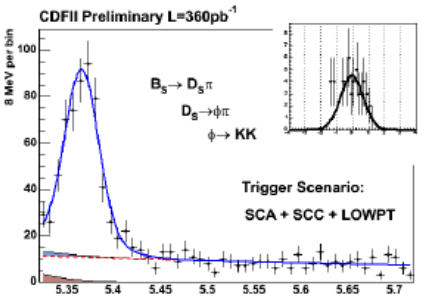
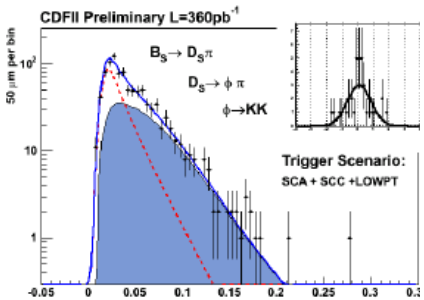
# Hadronic Lifetimes

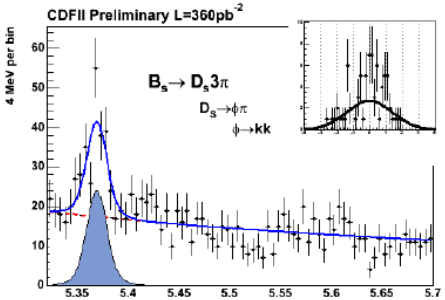
$B_s \to D_s^- \pi^+$

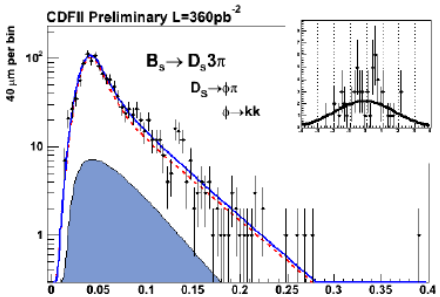



5.3 5.5

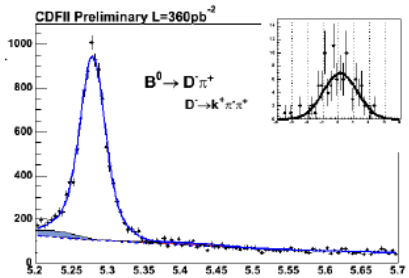
$B_s \to D_s^- \pi^+ \pi^- \pi^+$

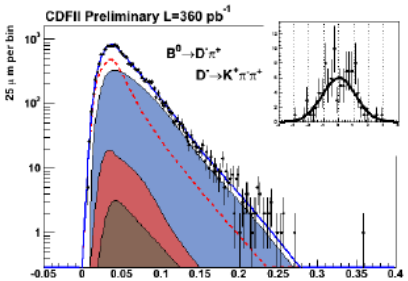


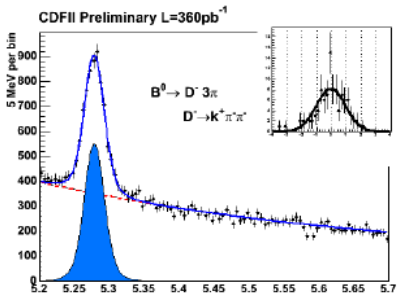

0.3

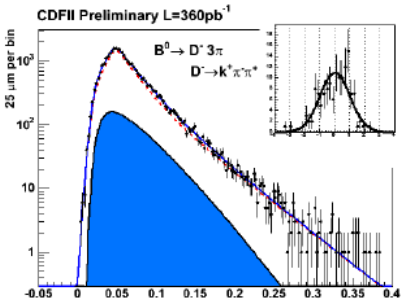
$B^0 \to D^\mp \pi^\pm$



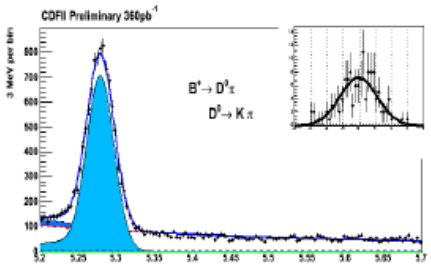



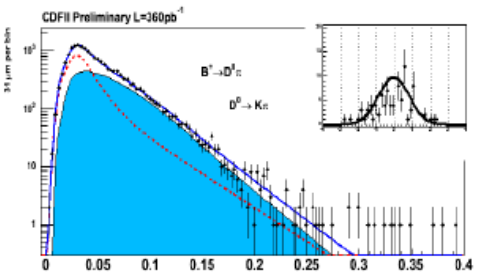

$B^0 \to D^\mp 3\pi^\pm$




$B^+ \to D^0 \pi^+$



# Lifetime values

## *lifetime values*

### *Single decay modes:*

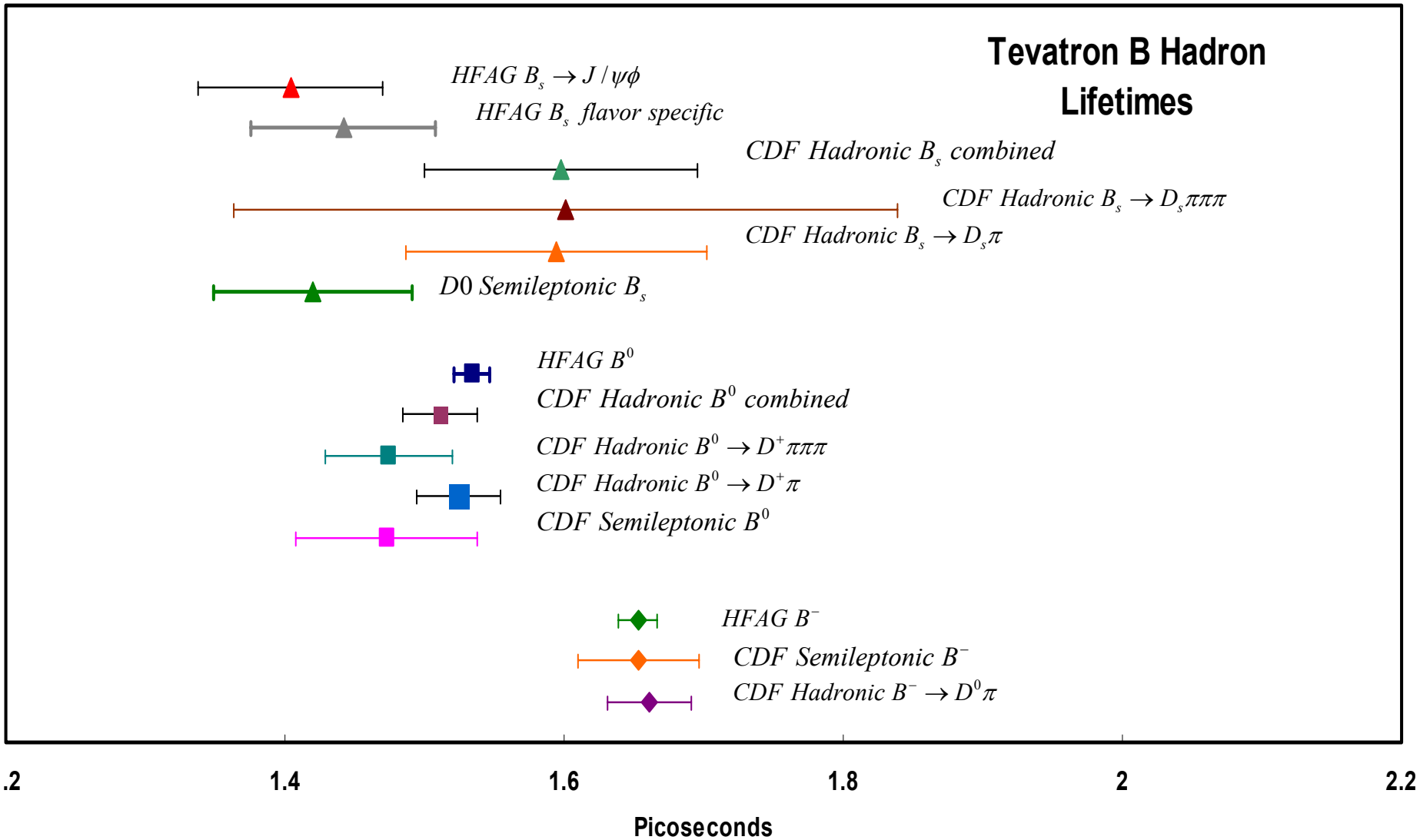
- $B^{\pm} \to D^0 \pi^{\pm}$ $(D^0 \to K^- \pi^+)$ — $498 \pm 8$ (stat.) $\pm 4$ (syst.) $\mu m$
- $B^0 \to D^{\mp} \pi^{\pm}$ $(D^- \to K^+ \pi^- \pi^-)$ — $457 \pm 8$ (stat.) $\pm 4$ (syst.) $\mu m$
- $B^0 \to D^{\mp} 3\pi^{\pm}$ $(D^- \to K^+ \pi^- \pi^-)$ — $442 \pm 13$ (stat.) $\pm 4$ (syst.) $\mu m$
- $B_S \to D_S^{\mp} \pi^{\pm}$ $(D_S^- \to \phi \pi^-)$ $(\phi \to K^+ K^-)$ — $479 \pm 32$ (stat.) $\pm 5$ (syst.) $\mu m$
- $B_S \to D_S^{\mp} 3\pi^{\pm}$ $(D_S^- \to \phi \pi^-)$ $(\phi \to K^+ K^-)$ — $480 \pm 71$ (stat.) $\pm 5$ (syst.) $\mu m$

### *Combined:*

$B^0 = 453 \pm 7$ (stat.) $\pm 4$ (syst.) $\mu m$

$B_S = 479 \pm 29$ (stat.) $\pm 5$ (syst.) $\mu m$

# Summary of new lifetime results

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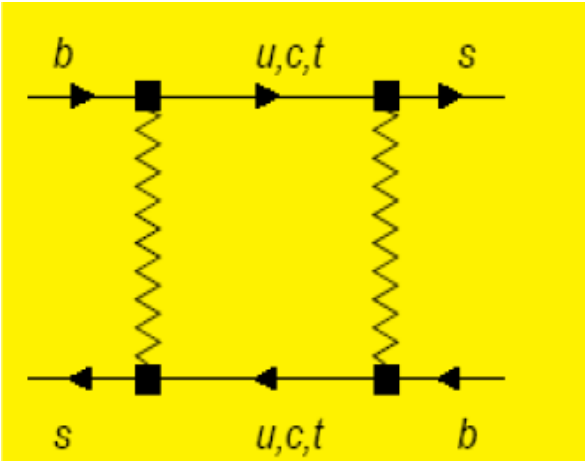
# $B_s$ System

Schrodinger Equation:

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




$M_{12}$ stems from the real part of the box diagram, dominated by top

$\Gamma_{12}$ stems from the imaginary part, dominated by charm

Heavy and light $B_s$ eigenstates are expected to have different widths

$$B_L = p|B_s\rangle + q|\overline{B}_s\rangle \approx cp\ odd$$

$$B_H = p|B_s\rangle - q|\overline{B}_s\rangle \approx cp\ even, \quad p^2 + q^2 = 1$$

# $\Delta\Gamma$ $B_s$

- Relation of matrix elements to decay and oscillation parameters:

$$\Delta m = M_H - M_L \approx 2|M_{12}|$$

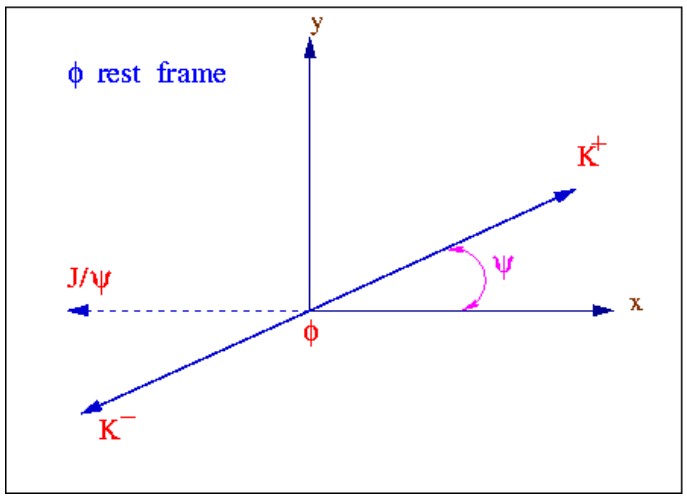
$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi \qquad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

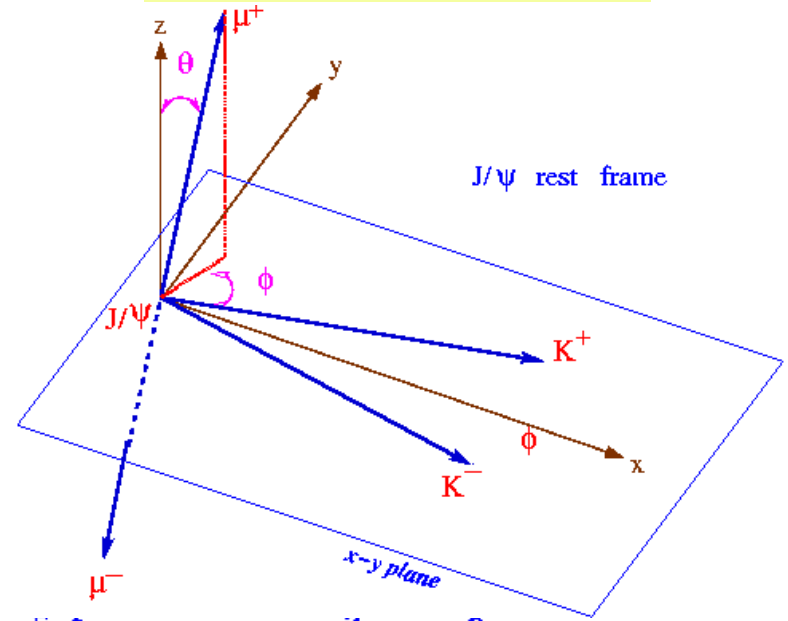
  In the Standard Model:
  - The CP violating phase, $\phi$ is expected to be small
  - Mass eigenstates are ~CP eigenstates with definite lifetimes
- The J/$\psi$ $\phi$ final state is a mixture of CP states
  L=0,2 – CP even ($A_0$,$A_{||}$)
  L=1 – CP odd ($A_\perp$)
- Assuming no CP violation in the $\mathbf{B_s}$ system, measure two $\mathbf{B_s}$ lifetimes, $\tau_L$ and $\tau_H$, (or $\Delta\Gamma/\Gamma$ and $\tau$) by simultaneously fitting time evolution and angular distribution in untagged $B_s \rightarrow$ J/$\psi$ $\phi$ decays
- CDF result last summer:

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

# Transversity Analysis

$\theta$ =transversity




$$\frac{d^3\Gamma \to J/\psi(\to l^+l^-)\,\phi(\to K^+K^-)}{d\cos\theta\, d\phi\, d\cos\psi\, dt} \propto \frac{9}{16\pi}\Big[\, 2|A_0(0)|^2 e^{-\Gamma_L t}\cos^2\psi(1-\sin^2\theta\cos^2\phi)$$

$$+\sin^2\psi\left\{|A_{\parallel}(0)|^2 e^{-\Gamma_L t}(1-\sin^2\theta\sin^2\phi) + |A_{\perp}(0)|^2 e^{-\Gamma_H t}\sin^2\theta\right\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi\left\{|A_0(0)||A_{\perp}(0)|\cos(\delta_2-\delta_1)e^{-\Gamma_L t}\sin^2\theta\sin^2 2\phi\right\}$$

$$+\left\{\frac{1}{\sqrt{2}}|A_0(0)||A_{\perp}(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\delta\phi$$

$$-\left\{\frac{1}{\sqrt{2}}|A_{\parallel}(0)||A_{\perp}(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\delta\phi\,\Big]\; H(\cos\psi)\,F(\phi)\,G(\cos\theta)$$

Full angular distribution

Sensitivity to CP violation if $\Delta\Gamma / \bar{\Gamma}$ is sizable

Detector acceptance

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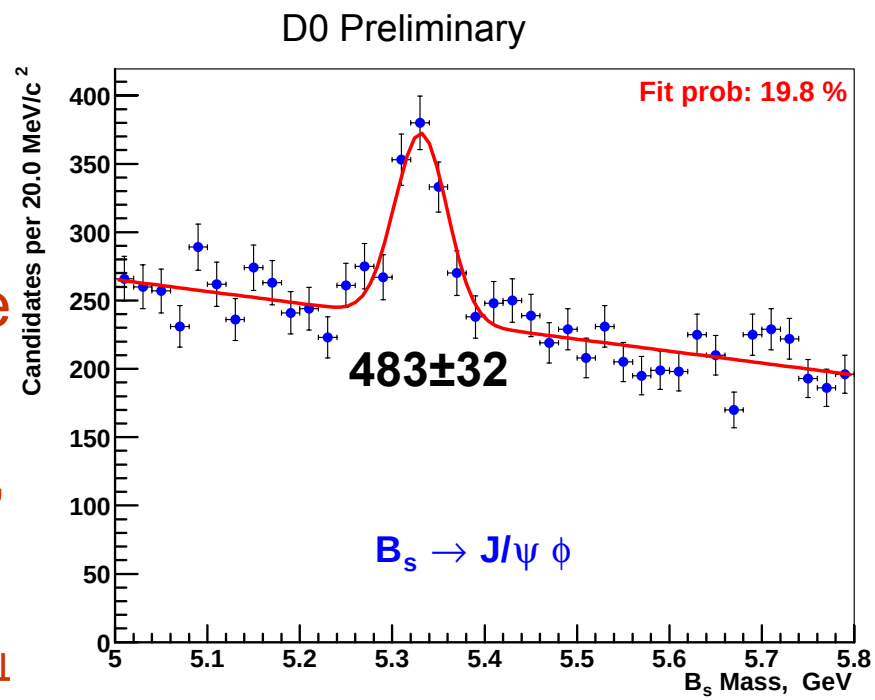
# $\Delta\Gamma$ B -> J/$\psi\phi$

- CDF summer result fit to $\theta,\phi,\psi$ angles giving $A_0$, $A_{||}$, $A_{\perp}$, phase, $R_{\perp} = |A_{\perp}(0)|^2$
- New D0 result integrates over the angles $\phi,\psi$ using MC efficiency
- Fit technique similar to lifetime fit, but adds angle dependence
- Provides values for $\tau$, $\Delta\Gamma$, and $R_{\perp}$ - no amplitudes or phase




$$\frac{d\Gamma(t)}{d\cos\theta} \propto \left(|A_0(t)|^2 + |A_{||}(t)|^2\right)\frac{3}{8}\left(1+\cos^2\theta\right) + \left|A_{\perp}(t)^2\right|\frac{3}{4}\sin^2\theta$$

Integral for flat Efficiency in $\phi,\psi$

# Likelihood Fit

- **Simultaneous fit to mass, proper decay length and transversity using an unbinned maximum log-likelihood method**

$$L = \prod_{i=1}^{N} \left[ f_{sig} F_{sig}^{i} + \left(1 - f_{sig}\right) F_{bkd}^{i} \right]$$

| | | |
|---|---|---|
| 1 | $f_{sig}$ | signal fraction |
| 1 | $c\tau = c/\bar{\Gamma}$, | $\bar{\Gamma} = (\Gamma_L + \Gamma_H)/2$ |
| 1 | $R_\perp$ | CP-odd fraction at t=0 |
| 1 | $\Delta\Gamma / \bar{\Gamma}$ | |

**Other free parameters**

| | |
|---|---|
| 2 | signal mass, width |
| 2 | bkg mass slope (1 prompt, 1 long-lived) |
| 1 | $\sigma(c\tau)$ scale |
| 6 | bkg $c\tau$ shape |
| 4 | bkg transversity (2 prompt +2 long-lived) |
| --- | |
| 19 | total |

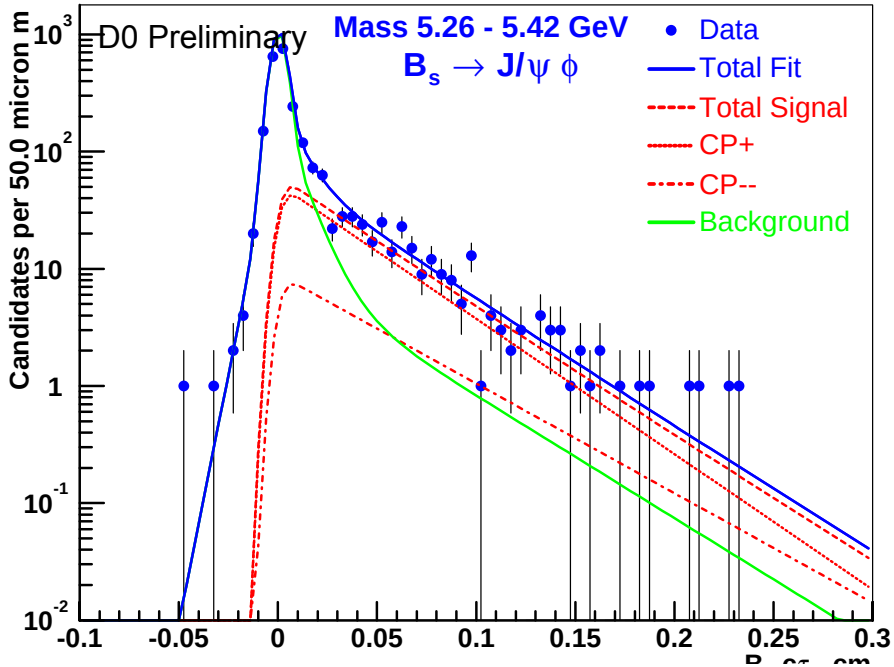
# $\Delta\Gamma$ Result

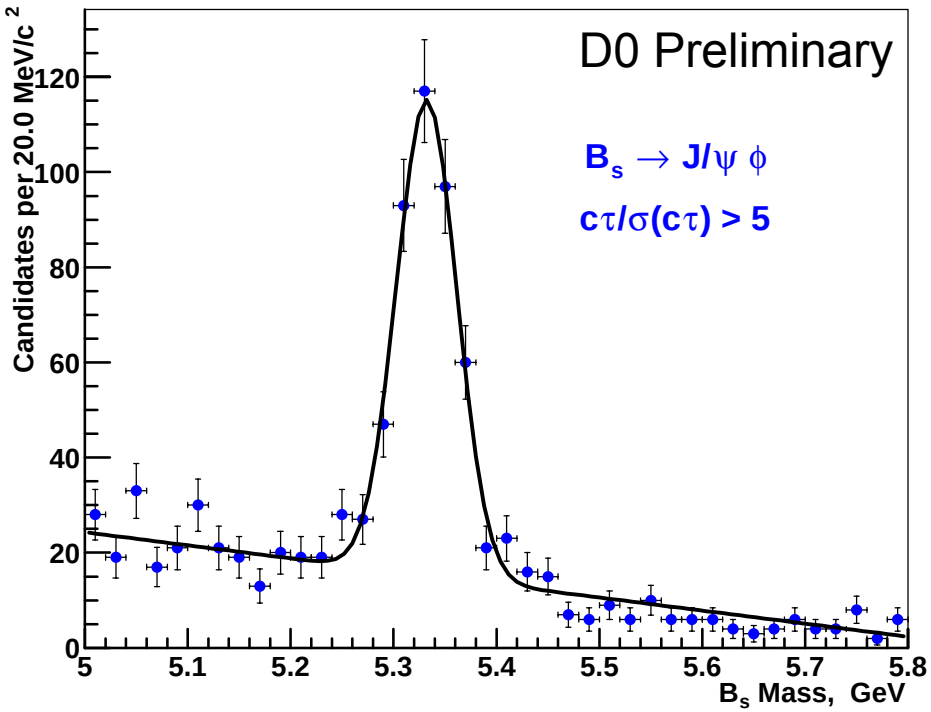
- Fit Result:

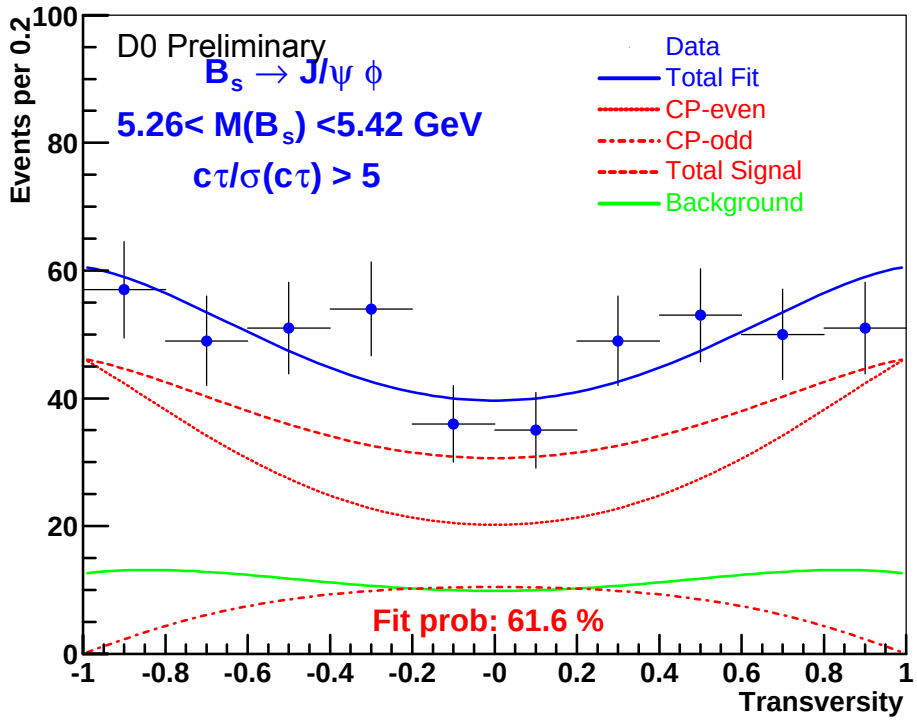
$$\bar{\tau}(B_s^0) = 1.39^{+0.13}_{-0.14} \pm 0.08\, ps$$

$$\frac{\Delta\Gamma}{\bar{\Gamma}} = 0.21^{+0.27}_{-0.40} \pm 0.20$$

$$R_\perp = 0.17 \pm 0.10 \pm 0.02$$



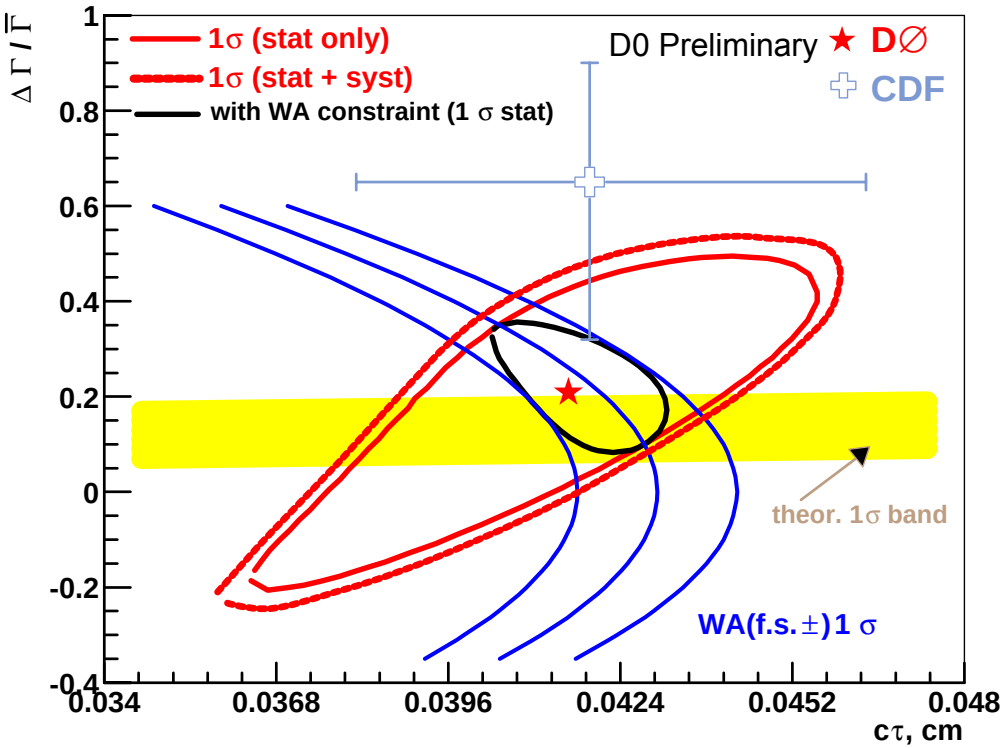
# Additional Constraints

- Include $\tau_{fs}$ constraint from semleptonic measurements:

$$\Gamma_{fs} = \overline{\Gamma}\left(\frac{1-\left(\Delta\Gamma/2\overline{\Gamma}\right)^2}{1+\left(\Delta\Gamma/2\overline{\Gamma}\right)^2}\right)$$

$$\overline{\tau_{fs}} = 1.43 \pm 0.05\, ps$$

$$\Rightarrow \frac{\Delta\Gamma}{\Gamma} = 0.23^{+0.16}_{-0.17}$$



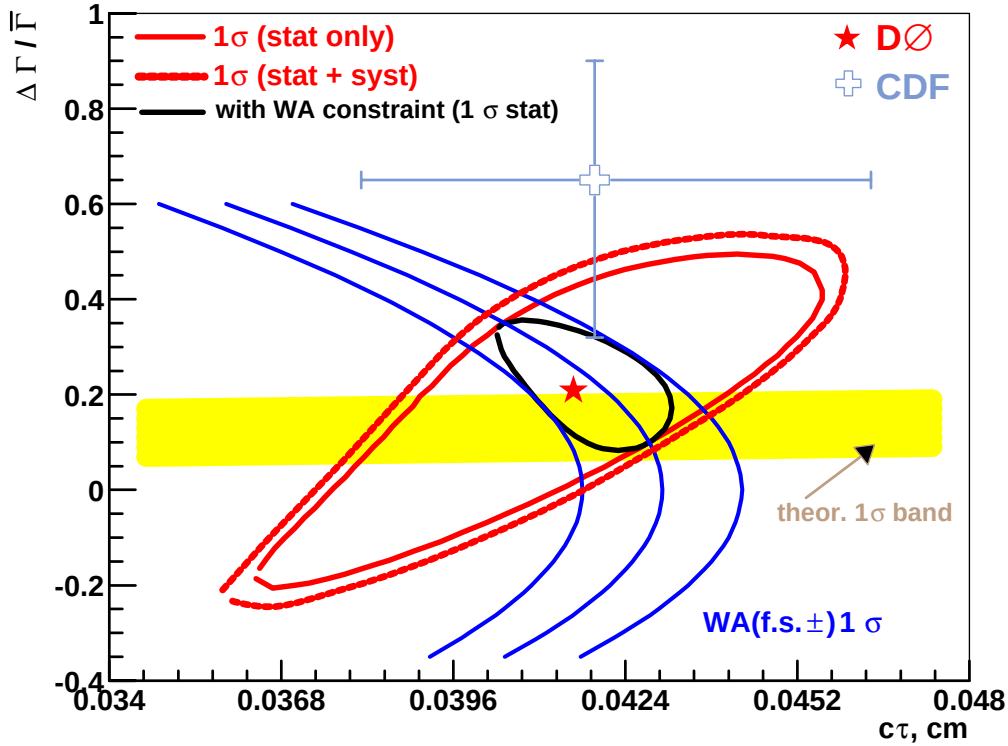

- We can also use the predicted value of $\Delta\Gamma_{\text{cp cons.}}$ =0.12±0.05 (Lenz hep-ph/0412007) with the semileptonic constraint to constrain a possible CP phase:

$$\frac{\Delta\Gamma}{\Gamma}_{measured} = \frac{\Delta\Gamma}{\Gamma}_{CPcons.} \cos^2(\phi)$$

$$|\cos\phi| = 1.46^{+0.73}_{-0.69}$$

# $\Delta\Gamma$ Comparisons

- D0 and CDF $\Delta\Gamma/\Gamma$ results are consistent
- D0 result is close to the theory prediction of 0.12±0.05
- The WA flavor specific lifetime provides significant improvement to $\Delta\Gamma$ and allows for a meaningful $\cos\phi$ constraint

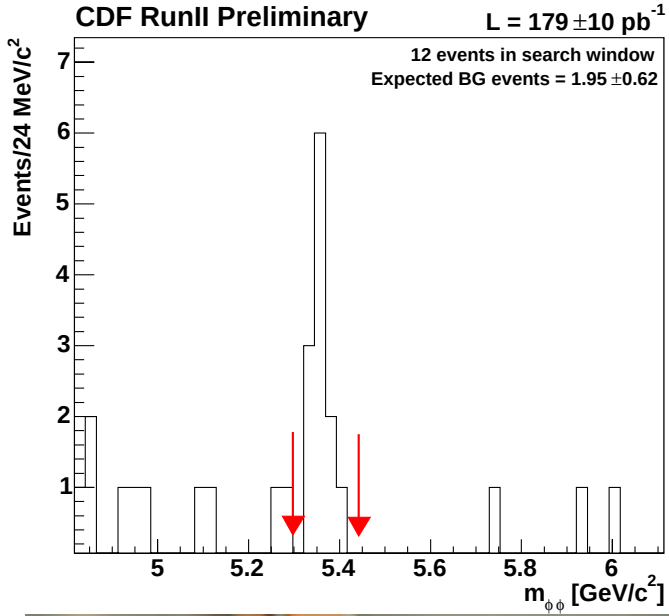


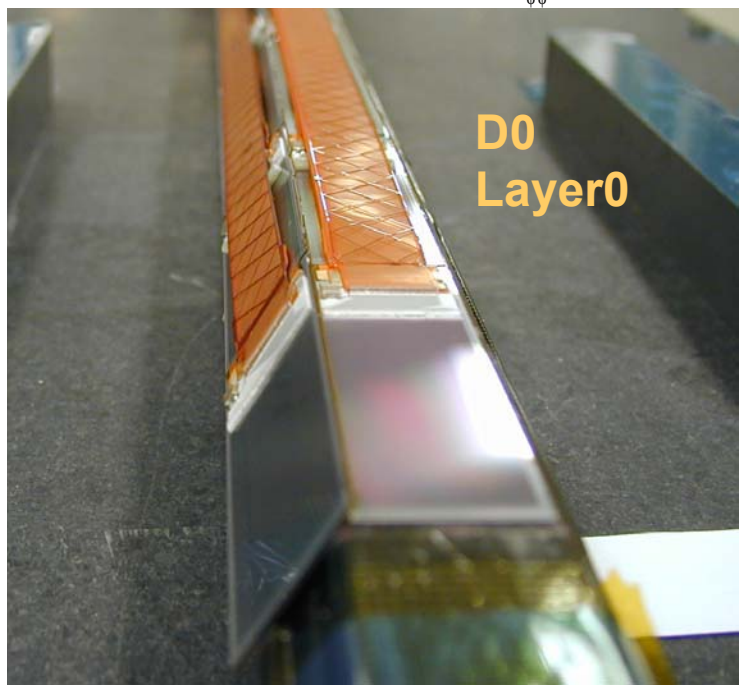

Including systematic errors:

| *Experiment* | $R_\perp$ | $\Delta\Gamma/\Gamma$ | $\bar{\tau}(ps)$ | $\tau_L$ | $\tau_H$ |
|---|---|---|---|---|---|
| *Aleph* | | | | $1.27 \pm 0.34$ | |
| *CDF RunII* | $0.125 \pm 0.08$ | $0.65^{+0.25}_{-0.33}$ | $1.40^{+0.15}_{-0.13}$ | $1.05^{+0.16}_{-0.13}$ | $2.07^{+0.58}_{-0.46}$ |
| *D0 RunII* | $0.17 \pm 0.10$ | $0.21^{+0.33}_{-0.45}$ | $1.39^{+0.15}_{-0.16}$ | $1.23^{+0.16}_{-0.13}$ | $1.52^{+0.39}_{-0.43}$ |

# Prospects

- D0 $\Delta\Gamma$ 3 angle analysis
- CDF $\Delta\Gamma$ updated analysis
  - $\phi\phi$, $\phi k^*$
- Explore CP violation ($\phi$)
- Continue to improve lifetime precision
  - Improved understanding of systematics
- Upgrades
  - D0 Layer 0 inside current silicon– improve $\sigma(c\tau)$, Silicon track trigger
  - DAQ – improve bandwidth
  - CDF Trigger and DAQ upgrades



# Backups

# *Systematic Uncertainties*

| Effect | Variation($\mu m$) | Variation($\mu m$) |
|---|---|---|
| | $B^0$ | $B_s$ |
| MC input $c\tau$ | negligible | negligible |
| $p_T$ reweight | 1.9 | 1.9 |
| Scale Factor | negligible | negligible |
| Bkg $ct$ description | 1.1 | 1.1 |
| Bkg fraction | 2.0 | 2.0 |
| I.P. correlation | 1.0 | 1.0 |
| Eff. parameterization | 1.5 | 1.5 |
| $L_{xy}$ significance | negligible | 2 |
| $\Delta\Gamma_s$ | - | 1.0 |
| Alignm. + others | 2.4 | 2.4 |
| Total | 4.2 | 4.7 |

# 3 Angles → 1 Angle

Inserting $H(\cos\psi) = 1$, and $F(\phi) = 1 + J\cos(2\phi) + K\cos2(2\phi)$, and integrating over $\cos\psi$ and $\phi$, we obtain a 1-angle time evolution:

$$\frac{d^3\Gamma \to J/\psi\,(\to l^+l^-)\,\phi(\to K^+K^-)}{d\cos\theta\, dt} = N\pi\Big[ (|A_0(0)|^2 + |A_{\parallel}(0)|^2)e^{-\Gamma_L t}(1+\cos^2\theta)$$

$$+ \frac{K}{2}\Big\{ (|A_0(0)|^2 + |A_{\parallel}(0)|^2)\, e^{-\Gamma_L t}(1+\cos^2\theta) \quad + 2\,|A_{\perp}(0)|^2 e^{-\Gamma_H t}\sin^2\theta \Big\}$$

$$- \frac{J}{2}(|A_0(0)|^2 - |A_{\parallel}(0)|^2)\, e^{-\Gamma_L t}\sin^2\theta \quad + 2\,|A_{\perp}(0)|^2 e^{-\Gamma_H t}\sin^2\theta \Big]\; G(\cos\theta)$$

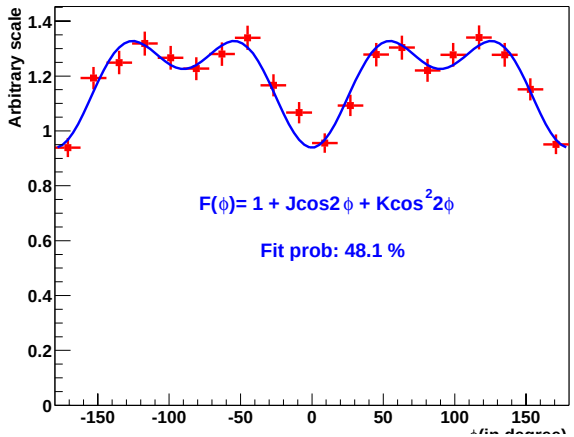
= 0.355 ± 0.066 (from CDF)

$$|A_0(0)|^2 + |A_{\parallel}(0)|^2 + |A_{\perp}(0)|^2 = 1$$

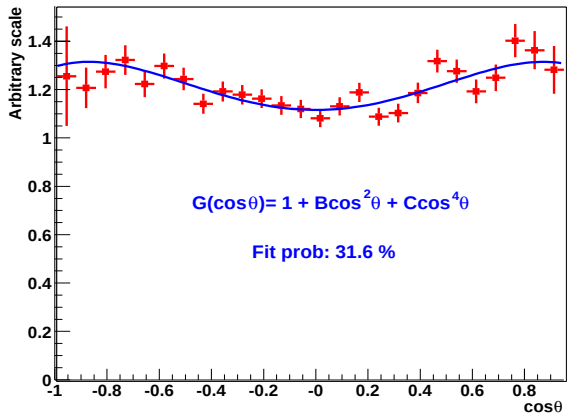
defining, $R_{\perp} = |A_{\perp}(0)|^2$

# MC Acceptance

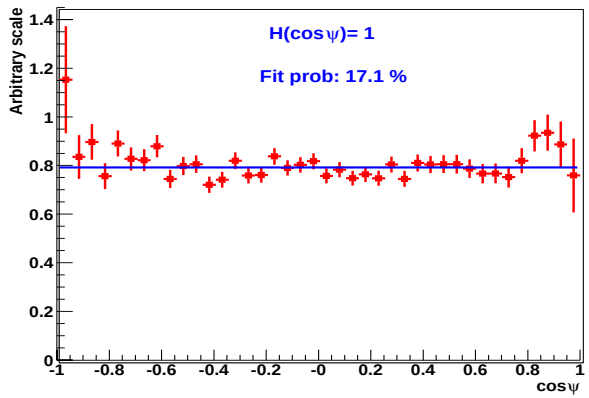
– $F(\phi) = 1 + J\cos(2\phi) + K\cos2(2\phi)$

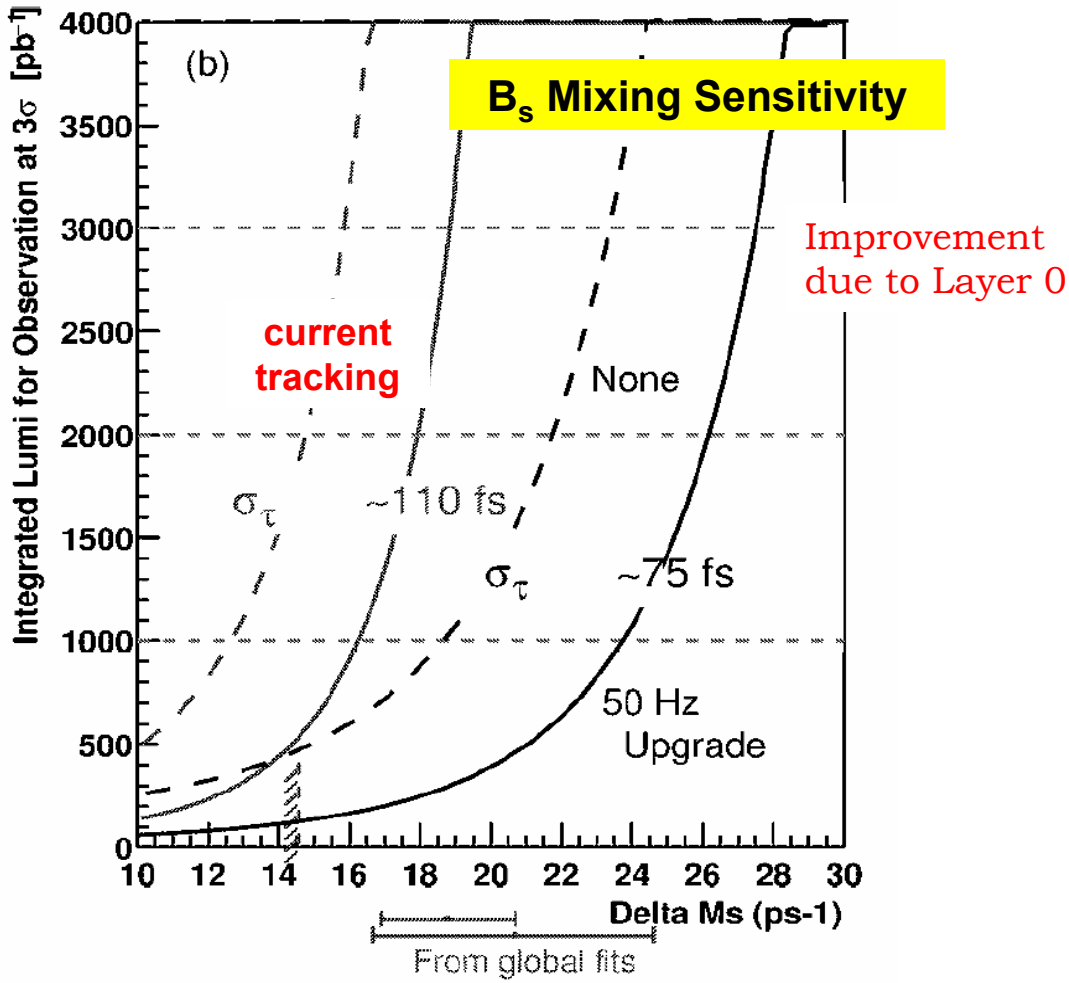



– $G(\cos\theta) = 1 + B\cos(2\theta) + C\cos(4\theta)$




– $H(\cos\psi)$ flat distribution




(b)
$B_s$ Mixing Sensitivity
Improvement due to Layer 0
current tracking
None
$\sigma_\tau$
~110 fs
$\sigma_\tau$
~75 fs
50 Hz Upgrade
Integrated Lumi for Observation at 3σ [pb⁻¹]
Delta Ms (ps-1)
From global fits
0
500
1000
1500
2000
2500
3000
3500
4000
10
12
14
16
18
20
22
24
26
28
30