

B Lifetimes and  $B\bar{B}$  Mixing  
Results and Prospects  
FPCCP2003

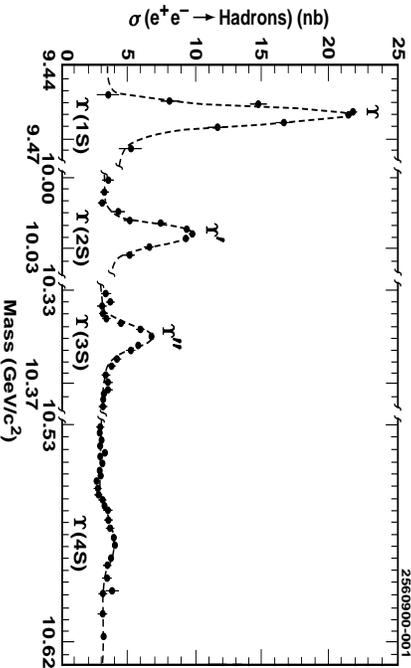
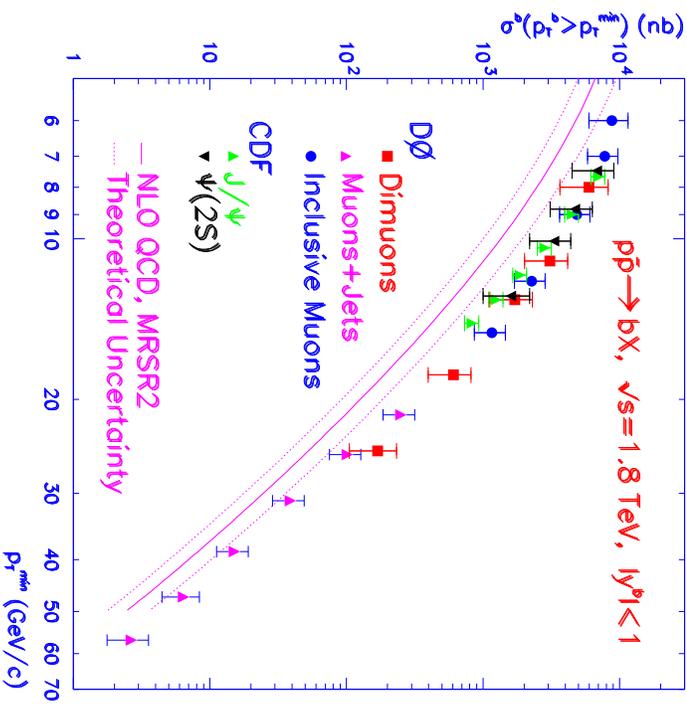
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Brookhaven National Laboratory  
(D0 Experiment)

June 4, 2003

Outline:

- B Lifetimes
- $B_d$  mixing
- $B_s$  mixing
- Conclusions

## B physics : Diverse environments



CLEO

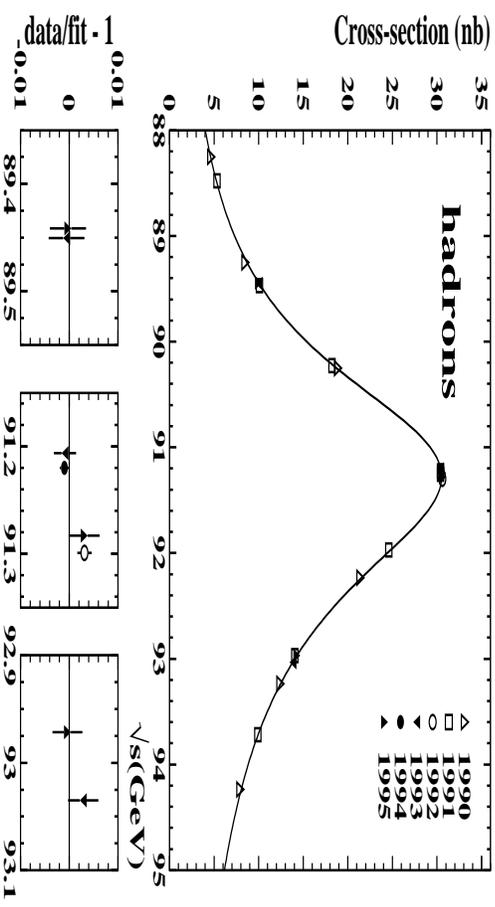
$$\sigma(p\bar{p} \rightarrow b\bar{b}) \approx 150 \mu\text{b at } \sqrt{s} = 2\text{TeV}$$

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

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

At the Tevatron:

All species produced, including  $B_s^0, B_c, \Lambda_b$   
 Environment not as clean as  $e^+e^-$  machines  
 Lower trigger efficiencies



OPAL

## Lifetimes

- **Lifetime difference** between  $D^+$ ,  $D^0$  underscored the importance of understanding non-leptonic decays
- **Precise lifetime meas.** can be used to extract weak parameters, *e.g.*  $f_B$
- **Inclusive decay rates** of heavy hadrons can be computed from first principles of QCD (via **Operator Product Expansion** - OPE)
- **OPE** involves Coefficients calculable within **short-distance physics**  
Expectation values of local operators given by **long distance physics** (obtained from symmetry, lattice QCD, quark models, QCD sum rules)  
Involves **inverse powers of heavy quark mass**
- **Leading non-perturbative correction**  $\approx (1/m_Q^2)$  (5% for B hadrons)
- Effects like **Pauli Interference**, **Weak Annihilation** arise at  $\approx (1/m_Q^3)$   
Main effect is to cause lifetime differences in hadrons of the same flavour

- For **Charm hadrons**, OPE is only semi-quantitative (Bigi, hep-ph 0001003)

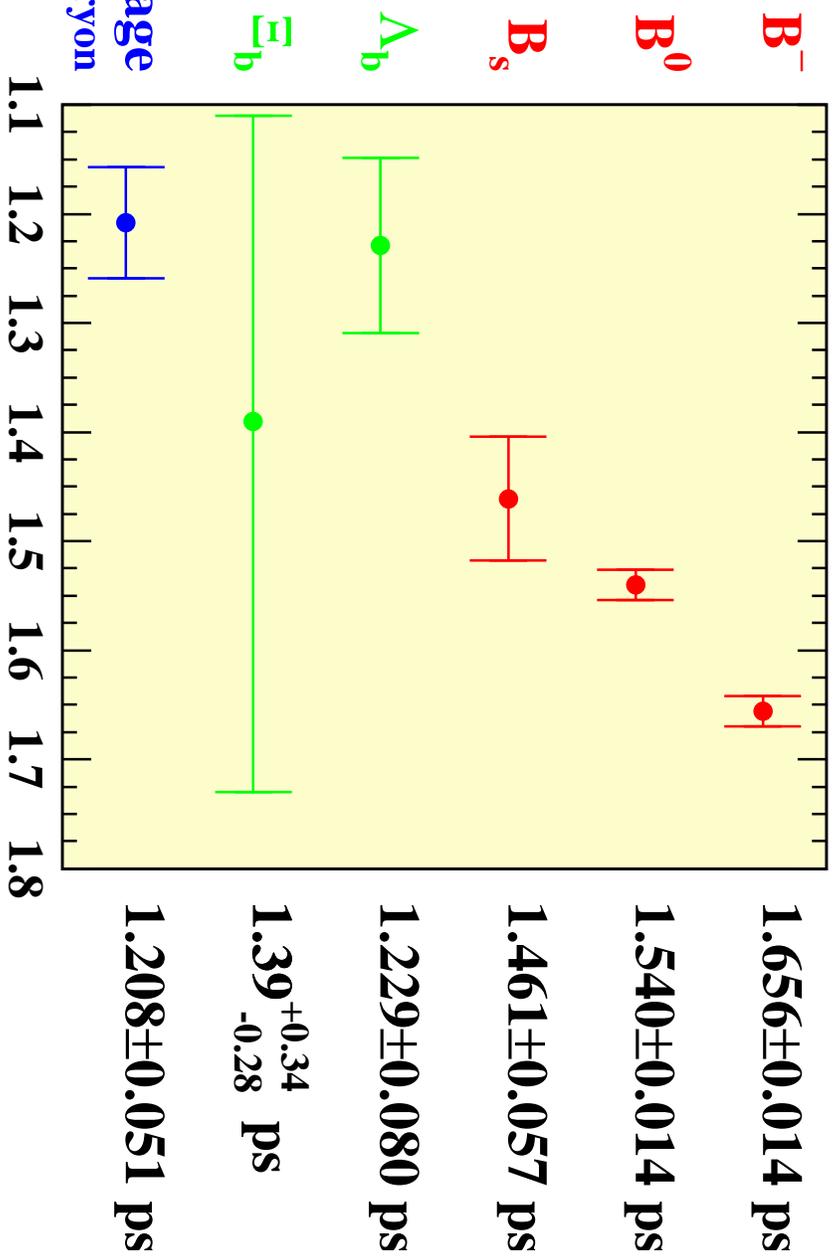
$$\tau(D^+)/\tau(D^0) \approx 2 \quad (\text{PDG: } 2.55 \pm 0.048) \text{ -PI}$$

$$\tau(D_s)/\tau(D^0) \approx 0.9 - 1.3 \quad (\text{PDG: } 1.21 \pm 0.017) \text{ -WA}$$

$$\tau(\Xi_c^+)/\tau(\Lambda_c^+) \approx 1.3 \quad (\text{PDG: } 2.2 \pm 0.20)$$

## B Lifetimes

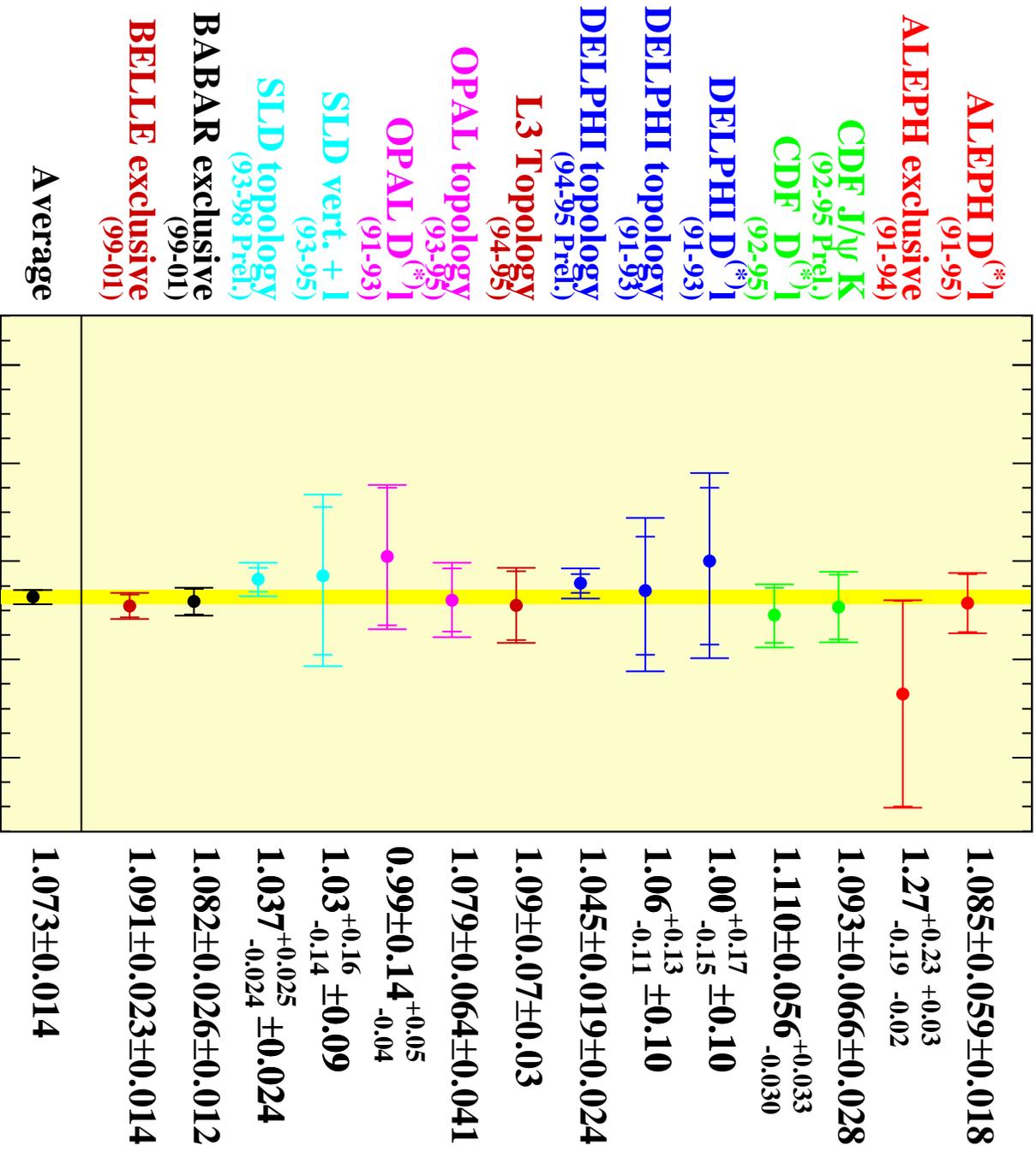
- Situation for **B hadrons** is better, because of larger  $m_Q$
- Most B hadrons have very similar lifetimes  
Using inputs from quenched lattice, NLO prediction:  
 $\tau(B^+)/\tau(B^0) = 1.053 \pm 0.016 \pm 0.017$   
(unquenching effects could be sizable) - Nierste, hep-ph/0209008
- OPE predicts  $\tau(B_c^+) \approx 0.5$  ps (PDG:  $0.46 \pm 0.17$ )  
absence of  $\sim \mathcal{O}(1/m_Q)$  corrections is crucial here
- $A_b$  is still a “puzzle”  
 $\tau(\Lambda_b)/\tau(B_d^0) \approx 0.9 - 1.0$  (PDG:  $0.80 \pm 0.05$ )
- Expectation for  $\tau(B_s)/\tau(B_d) \approx 1.0 \pm \mathcal{O}(0.01)$
- Need experimental results for other beauty baryons, e.g.  $\Xi_b$
- Ability to measure lifetimes necessary ingredient for time-dependent measurements of **Mixing**, **CP violation**
- For  $B_d$ ,  $B_s$  we can also look at lifetime differences between **Mass eigenstates** (more later)

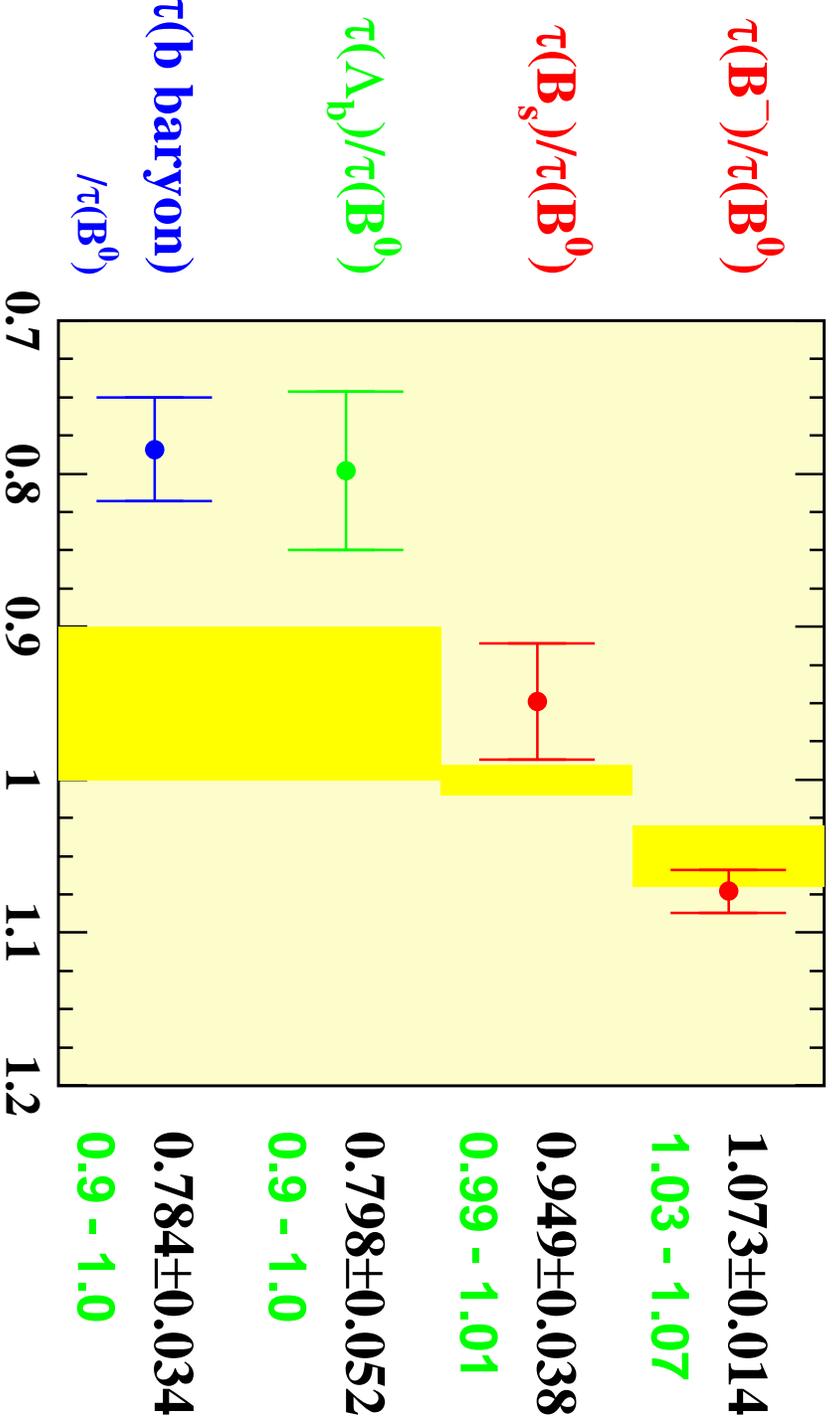


B Lifetime  
Working Group  
July 2002

$\tau$  (ps)

Exclusive and Inclusive measurements for  $B^0, B^+, B_s$   
Inclusive measurements for  $A_b, E_b, B_c$



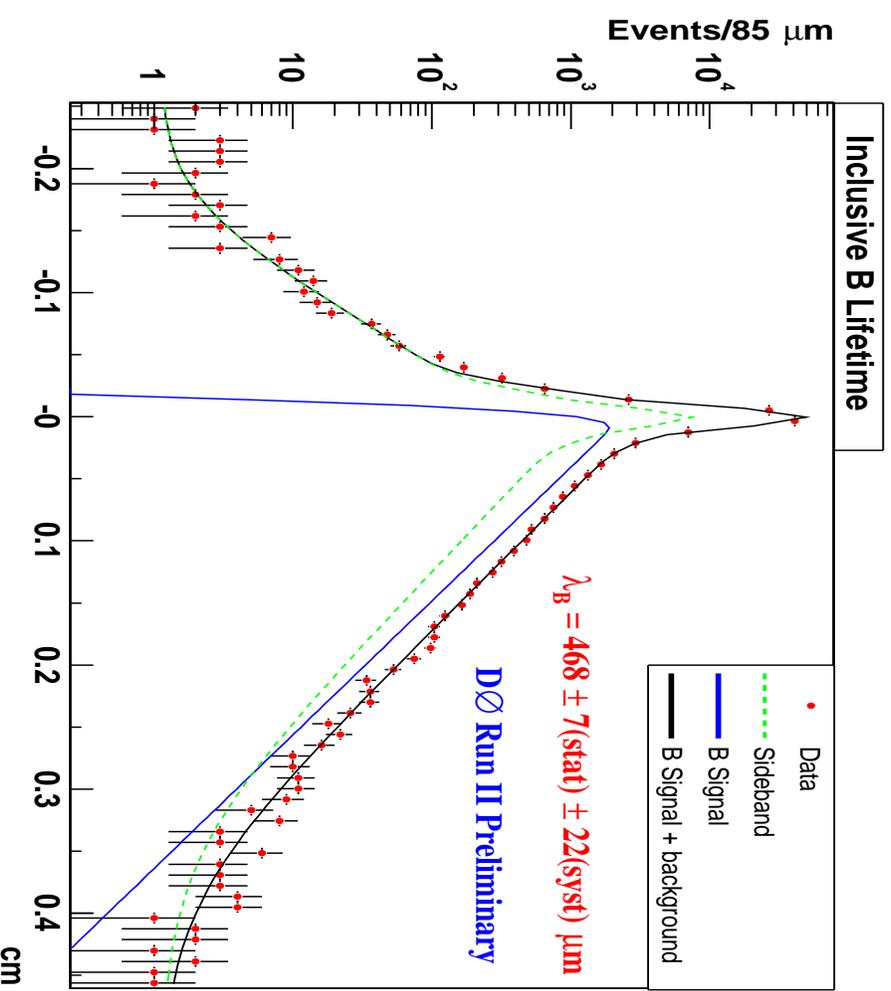
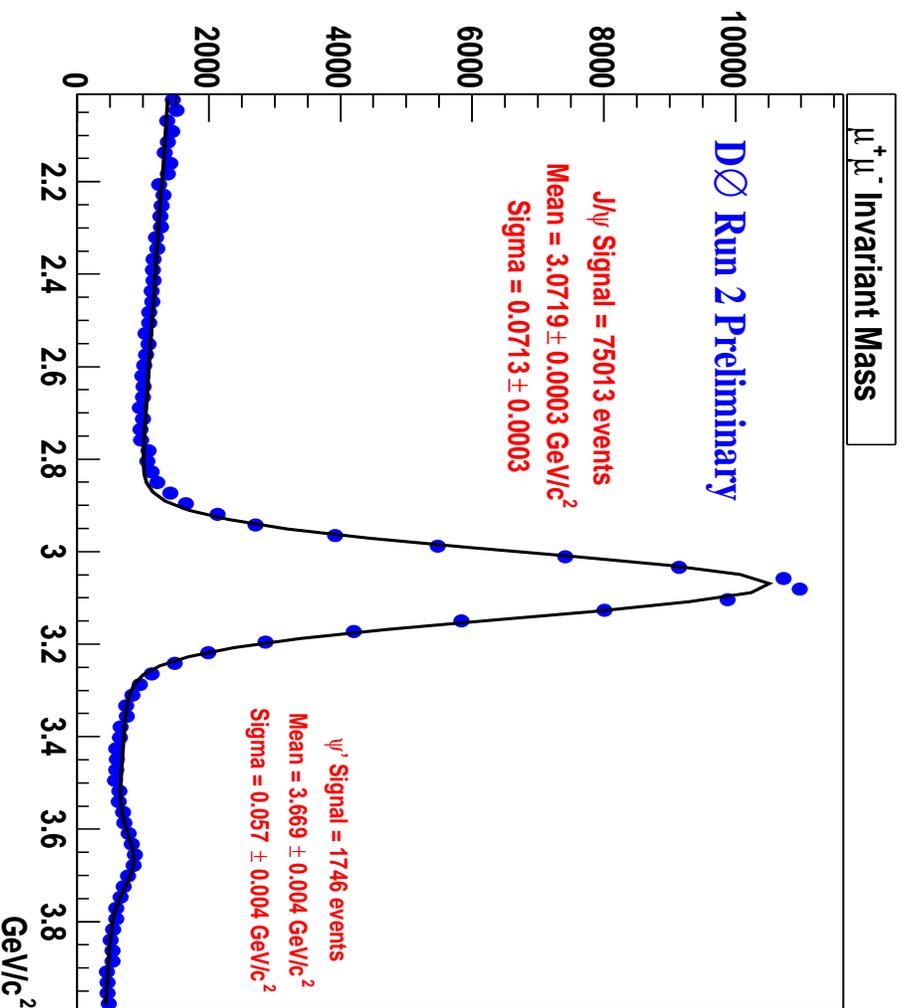


B Lifetime  
Working Group  
July 2002

Theory predictions

## New Results from the Tevatron

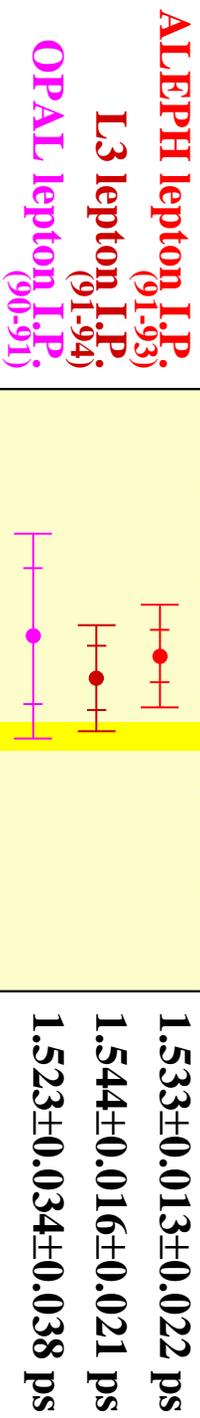
**D0 is new** to this arena  
 $(\mathcal{L} \approx 45\text{pb}^{-1})$



**Correction Factor** needed to infer B momentum from  $J/\psi$  vertex

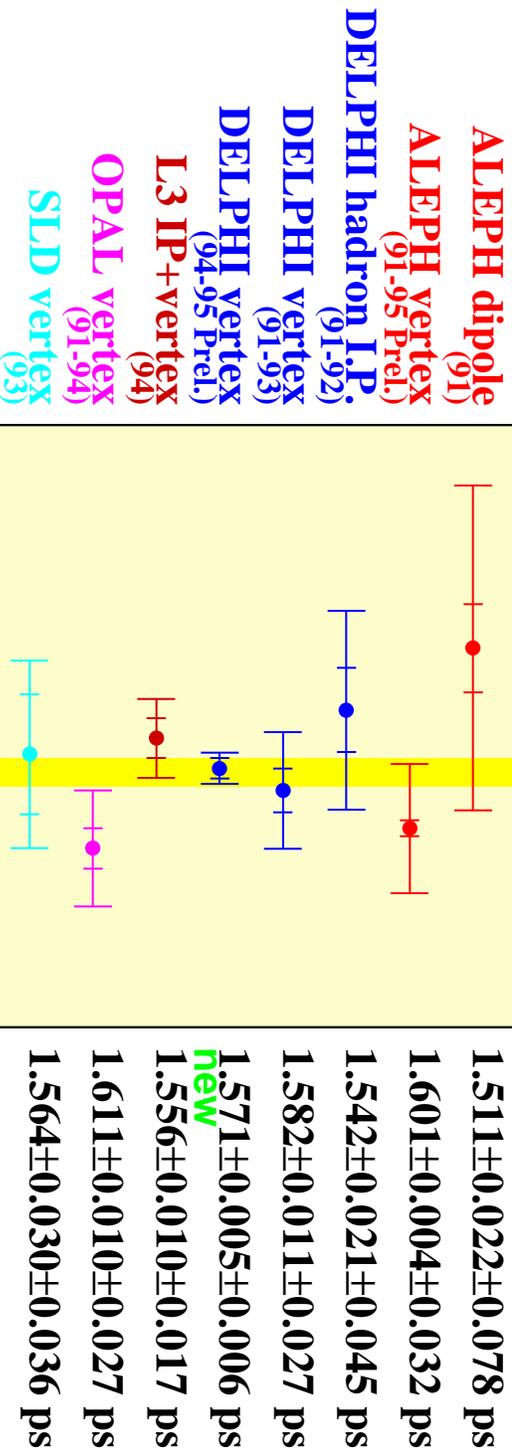
$$\langle \tau \rangle = 1.561 \pm 0.024(\text{stat}) \pm 0.074(\text{syst}) \text{ ps}$$

$$(B \text{ WG: } 1.573 \pm 0.007)$$



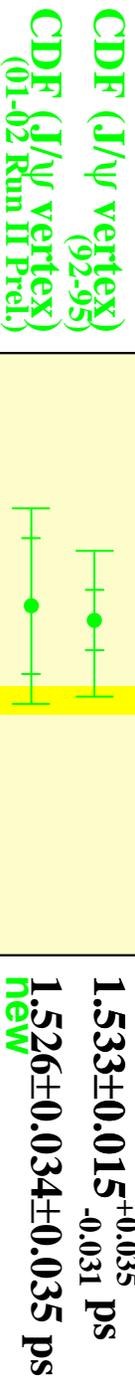
**Average**  
above 3

$1.537 \pm 0.02$  ps



**Average**  
above 8

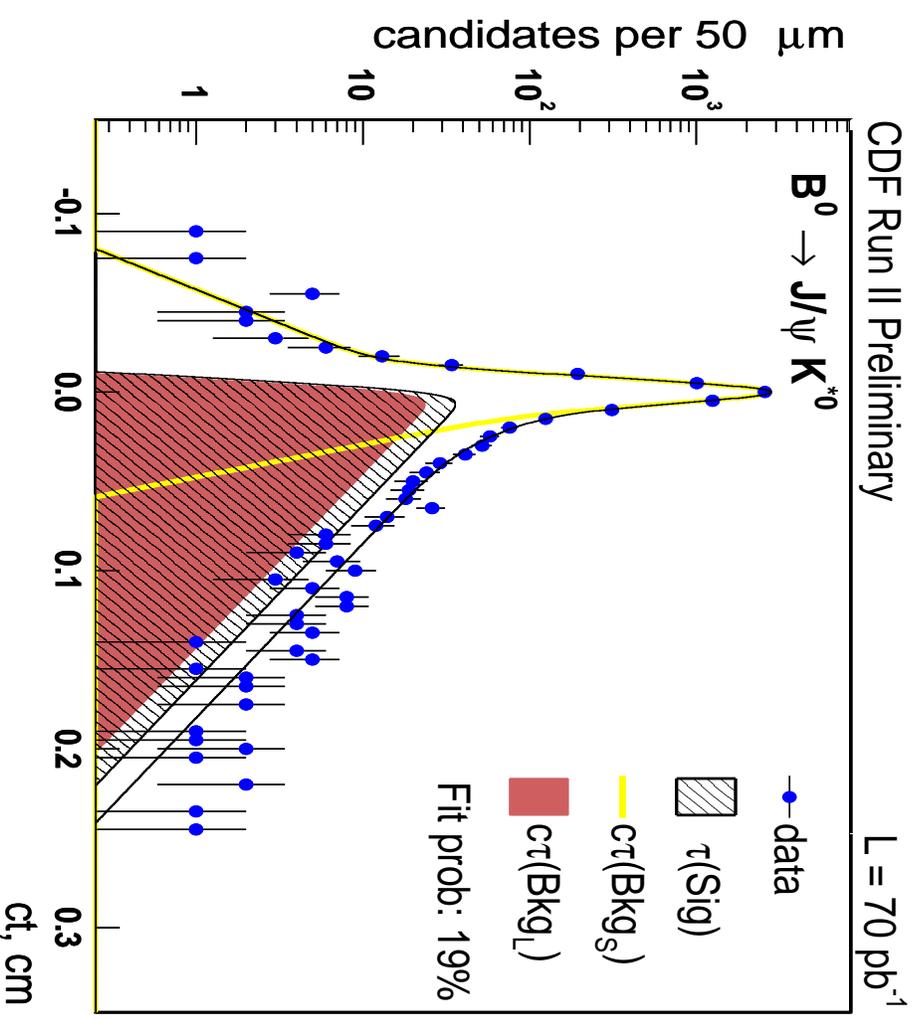
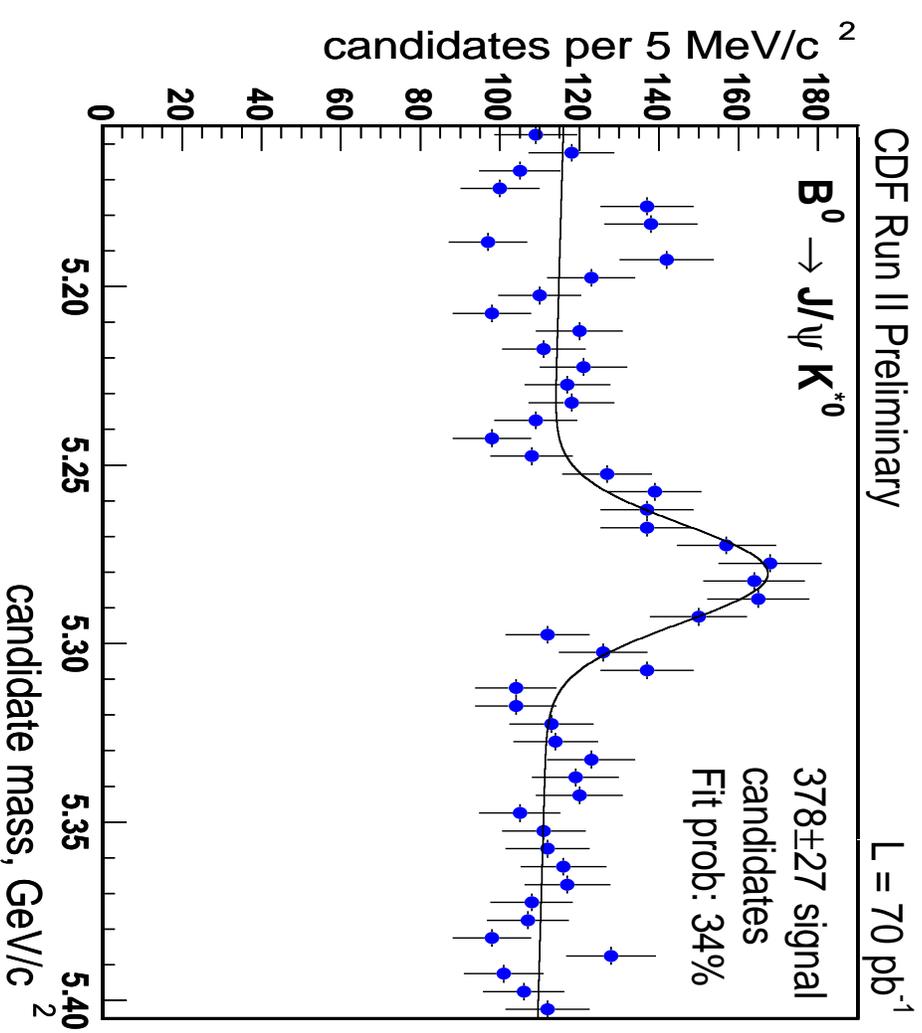
$1.576 \pm 0.008$  ps



**Average**

$1.573 \pm 0.007$  ps

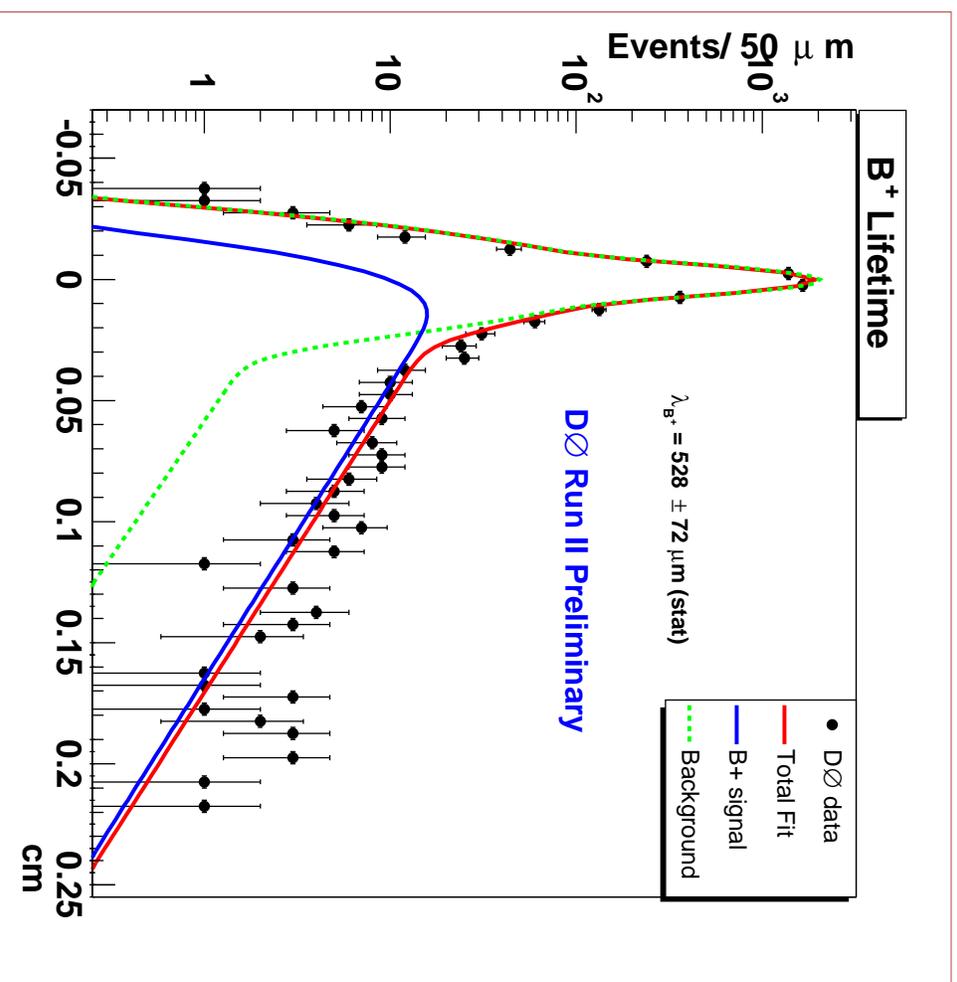
1.4 1.45 1.5 1.55 1.6 1.65 1.7



$$\langle \tau \rangle = 425 \pm 28 \pm 6 \mu\text{m}$$

$$(\text{B WG: } 462 \pm 4 \mu\text{m})$$

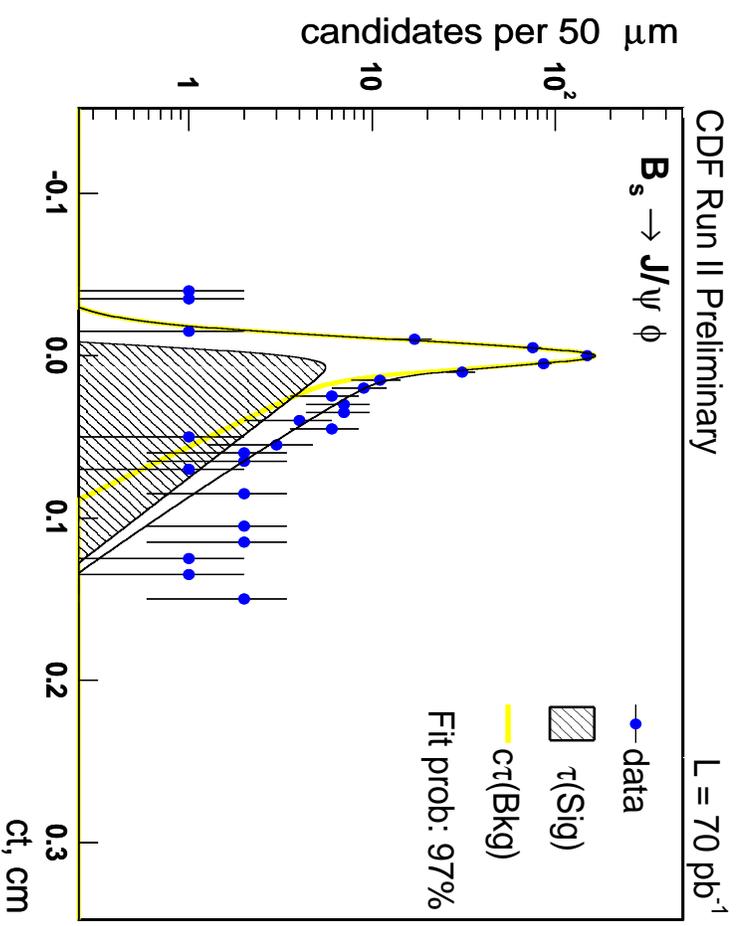
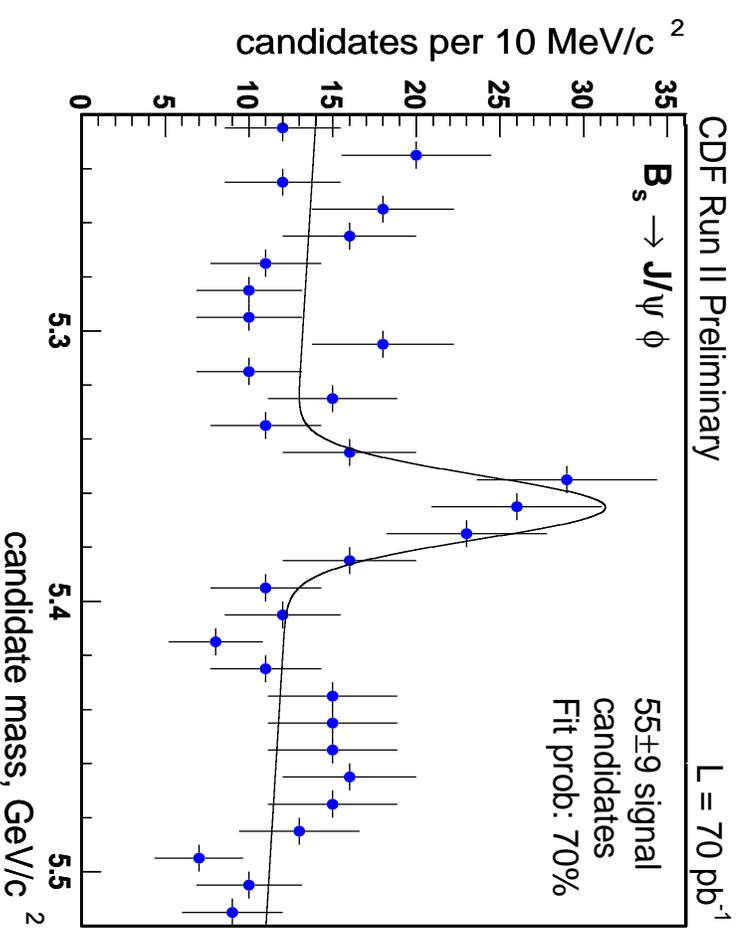
$\lambda_{B^\pm}$  distribution ( $\mathcal{L} \approx 45\text{pb}^{-1}$ )



$\langle \tau \rangle = 1.76 \pm 0.24(\text{stat}) \text{ ps}$  (B WG  $1.656 \pm 0.014$ )

CDF  $\langle \tau \rangle = 1.57 \pm 0.07 \pm 0.02 \text{ ps}$  ( $\mathcal{L} \sim 70 \text{ pb}^{-1}$ )

All previous measurements of  $B_s$  (except CDF) and  $A_b$  lifetimes were with inclusive decays  
 Both CDF and D0 are fully reconstructing these decays

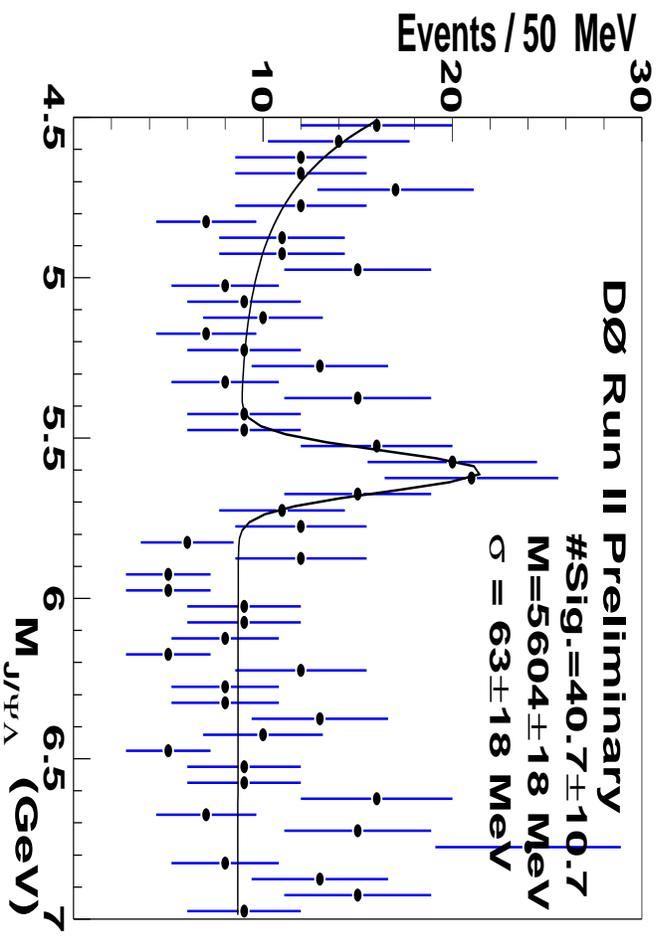
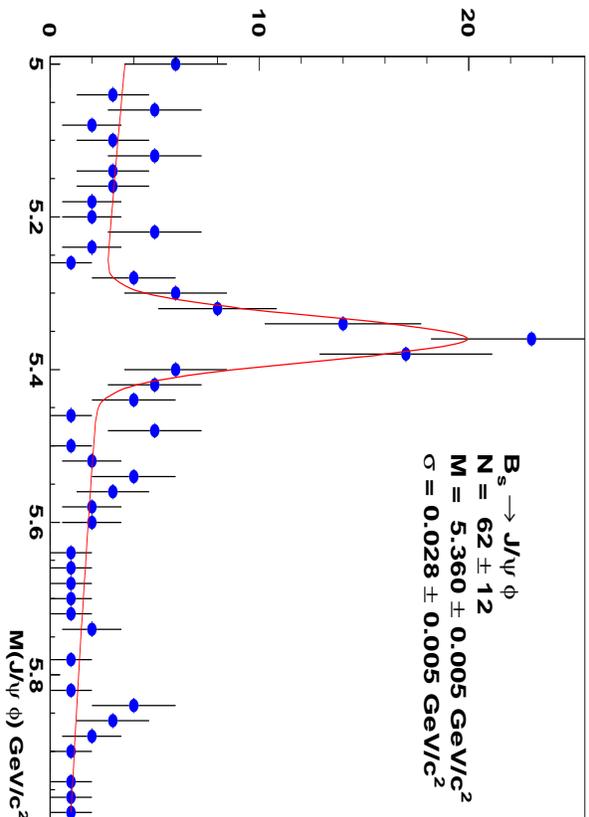


$$\langle \tau \rangle = 379 \pm 59 \pm 6 \mu\text{m}$$

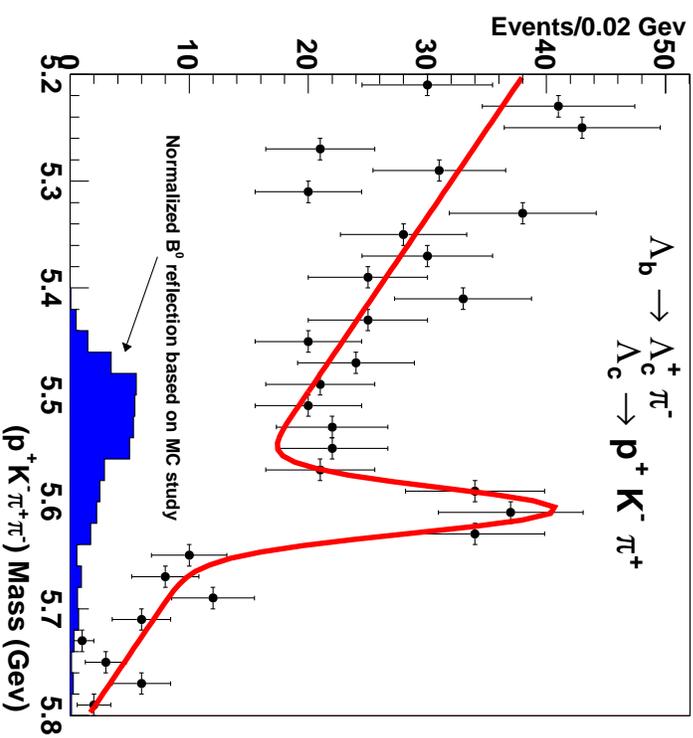
$$(B \text{ WG: } 438 \pm 17 \mu\text{m})$$

$(\mathcal{L} \approx 45\text{pb}^{-1})$

**D0 Run1 Preliminary**



**CDF Run 2 PRELIMINARY 65pb<sup>-1</sup>**



Event estimates for  $1 \text{ fb}^{-1}$

$B_s \rightarrow J/\psi \Phi \approx 1000 - 1500$  events

$\Lambda_b \rightarrow J/\psi \Lambda \approx 1000$  events

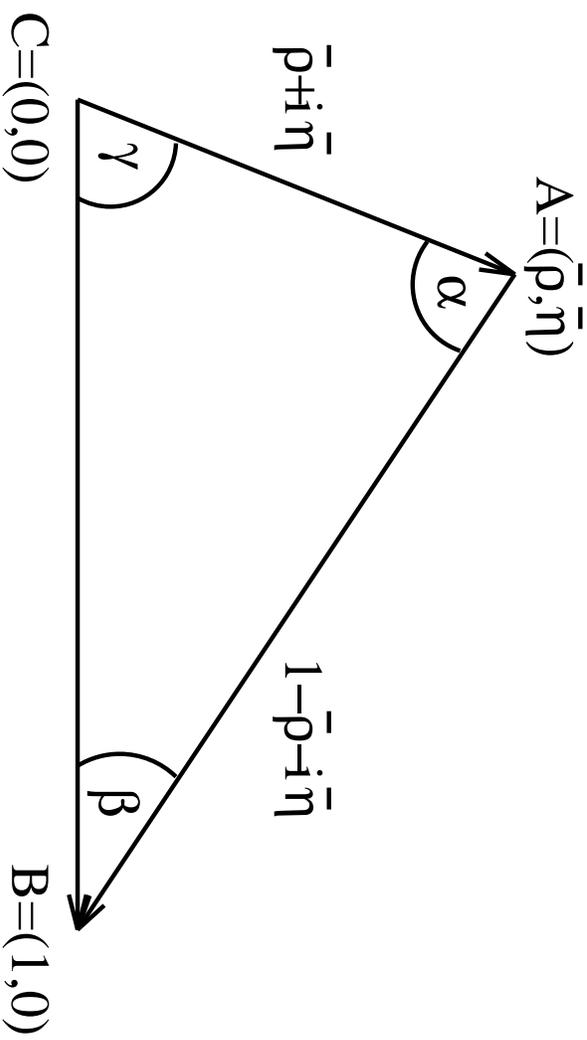
$\rightarrow \Lambda_c \pi \approx 1000$  events

$B_c \rightarrow J/\psi l \nu \approx 300 - 1000$  events

$\rightarrow J/\psi \pi \approx 50 - 100$  events

Stay tuned for lifetime analyses!

## $B\bar{B}$ oscillations

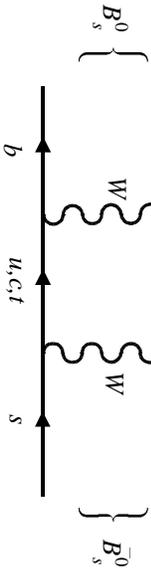
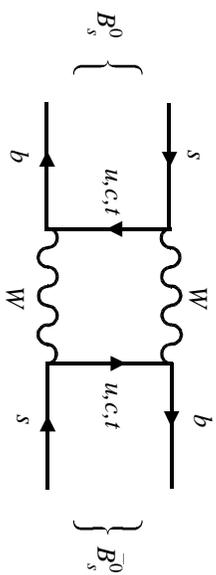


where sides  $CA$  and  $BA$  are given by  $R_b, R_t$  respectively

$$R_b \equiv \frac{|V_{ud} V_{ub}^*|}{|V_{cd} V_{cb}^*|} = \sqrt{\bar{\rho}^2 + \bar{\eta}^2} = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right|,$$

$$R_t \equiv \frac{|V_{td} V_{tb}^*|}{|V_{cd} V_{cb}^*|} = \sqrt{(1 - \bar{\rho})^2 + \bar{\eta}^2} = \frac{1}{\lambda} \left| \frac{V_{td}}{V_{cb}} \right|.$$

$R_t$  can be obtained from  $B_d, B_s$  oscillations



Proceeds via **second order weak transition**

**$B\bar{B}$  mixing** very important in constraining CKM

- Side **CA** of the **Unitarity triangle** ( $\propto |V_{td}|$ ) is also

$$R_t = 0.88 \left[ \frac{\xi}{1.18} \right] \sqrt{\frac{18.0/\text{ps}}{\Delta M_s}} \sqrt{\frac{\Delta M_d}{0.5/\text{ps}}}, \quad \xi = \frac{\sqrt{B_{B_s} F_{B_s}}}{\sqrt{B_{B_d} F_{B_d}}}$$

- **Mass eigenstates** can be written in terms of flavour eigenstates

$$\begin{aligned} |B_s^L\rangle &= p|B_s^0\rangle + q|\bar{B}_s^0\rangle \\ |B_s^H\rangle &= p|B_s^0\rangle - q|\bar{B}_s^0\rangle \end{aligned}$$

- $\Delta M_s \equiv M_H - M_L$ ,  $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$

- An initially pure  $B_s^0$  state can evolve in time

$$|B_s^0(t)\rangle = g_+(t)|B_s^0\rangle + g_-(t)\frac{p}{q}|\bar{B}_s^0\rangle$$

$$|\bar{B}_s^0(t)\rangle = g_-(t)\frac{q}{p}|B_s^0\rangle + g_+(t)|\bar{B}_s^0\rangle$$

- Unmixed/Mixed probability can be written as

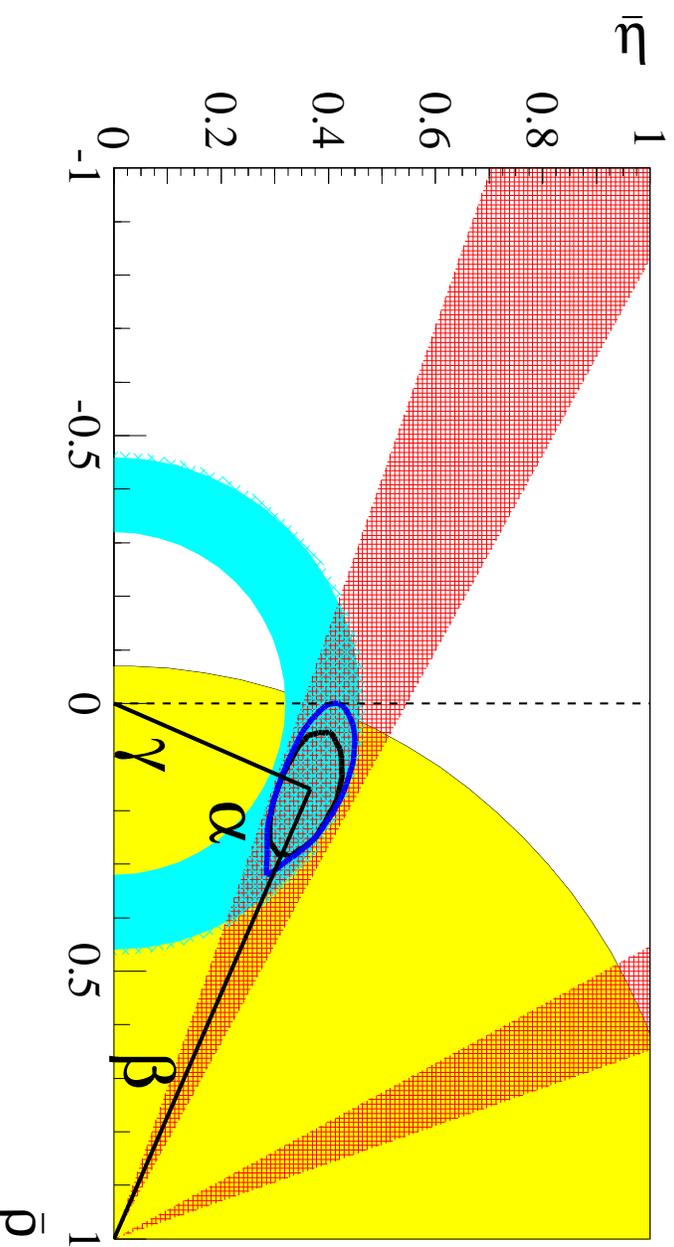
$$\mathcal{P}_{u,m}(t) = \frac{\Gamma_s e^{-\Gamma_s t}}{2} \left[ \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \cos(\Delta m_s t) \right]$$

- For  $\Delta\Gamma_s \approx 0$  (SM expectation)

$$\mathcal{P}_{u,m}(t) = \frac{\Gamma_s e^{-\Gamma_s t}}{2} [1 \pm \cos(\Delta m_s t)]$$

- Can also make time-integrated mixing measurement  
 $\chi_d$  (at  $\Upsilon(4S)$ ) or  $\bar{\chi} = f_d \chi_d + f_s \chi_s$  (at LEP, Tevatron)  
 where  $\chi_{d(s)}$  is a function of  $\Delta m_{d(s)}, \Delta\Gamma_{d(s)}, \frac{q}{p} \frac{\bar{A}_f}{A_f}$

- Study of **B hadrons** lead to  $\eta$ ,  $V_{ub}/V_{cb}$ ,  $V_{cb}$ ,  $V_{td}$ ,  $V_{ts}$  -  $V_{td}$ ,  $V_{ts}$  via  $B_d$ ,  $B_s$  oscillations  
 $\eta$  can be inferred from CP violation in  $B_d \rightarrow J/\psi K_s^0$
- Yellow band is from  **$B\bar{B}$  mixing measurements**
- $\bar{\rho} > 0$  is from the lower limit on  $B_s$  mixing



Narrower region is the 95% (SM) allowed region - [Buras hep-ph/0210291](#)

## Experimental Considerations

For time-dependent mixing measurements, need

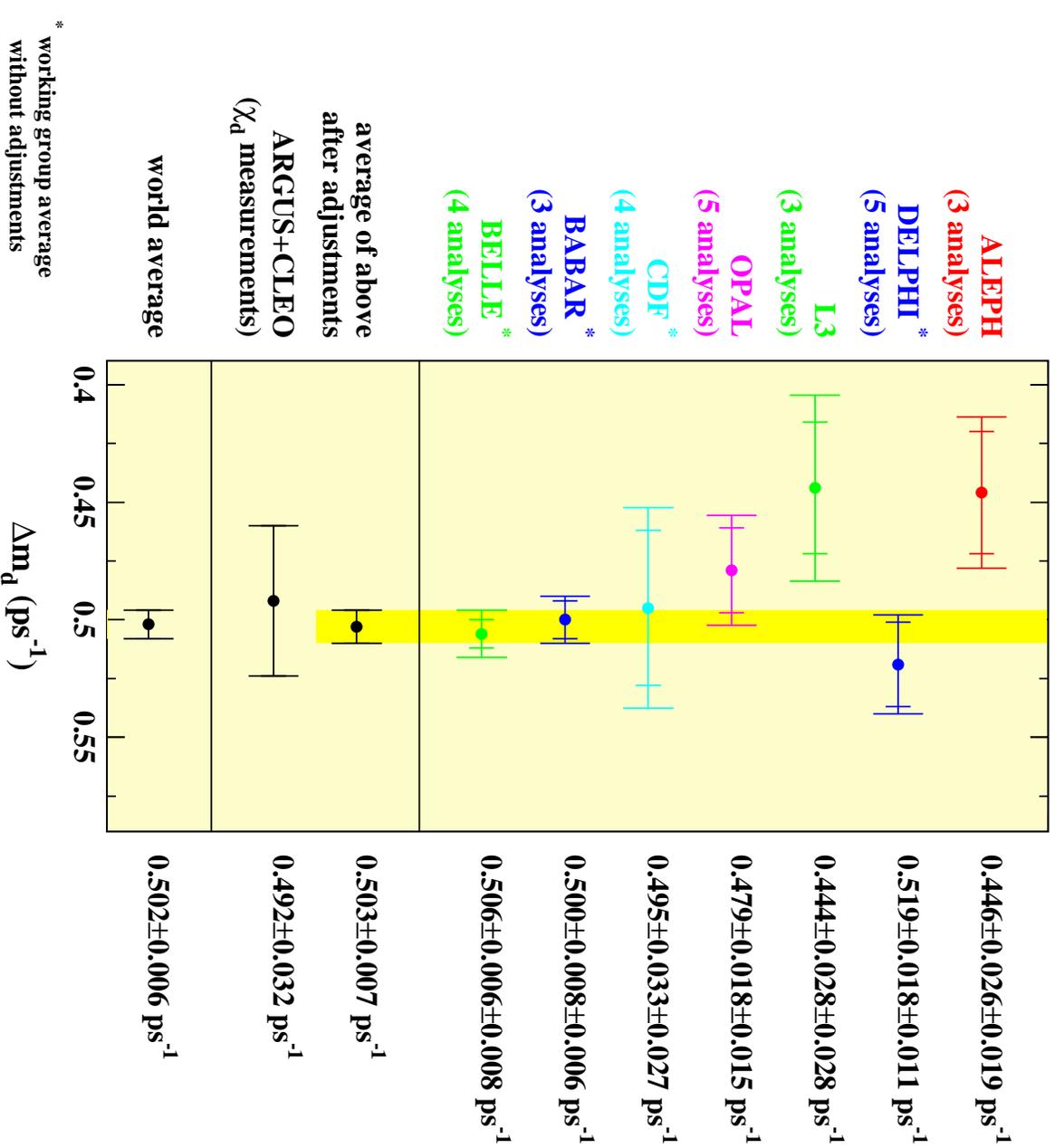
- Final state reconstruction  
 $B \rightarrow J/\Psi X, D^{(*)}l\nu, D^{(*)}(n\pi), \dots$
  - Proper time measurement
  - Flavour tagging at production and decay
  - Measure asymmetry  $\mathcal{A}_f(t)$ ,
- Crucial component is proper time resolution,  $t = m_B L/p$ ,

$$\sigma_t = \frac{m_B}{p} \sigma_L \oplus \frac{\sigma_p}{p}$$

- Significance of mixing measurement (likelihood fit to  $\mathcal{A}_f(t)$ )

$$\mathcal{S} = \sqrt{\frac{N\epsilon D^2}{2}} e^{-(\Delta m_s \sigma_t)^2/2} \sqrt{\frac{S}{S+B}}$$

# $B_d \bar{B}_d$ Mixing Results (Winter 2003 conferences)



Although  $\Delta m_d$  is known to **1.4% accuracy**, theoretical uncertainties due to  $f_{B_d} \sqrt{B_{B_d}} = 230 \pm 40$  MeV, dominate in the extraction of  $|V_{td}|$



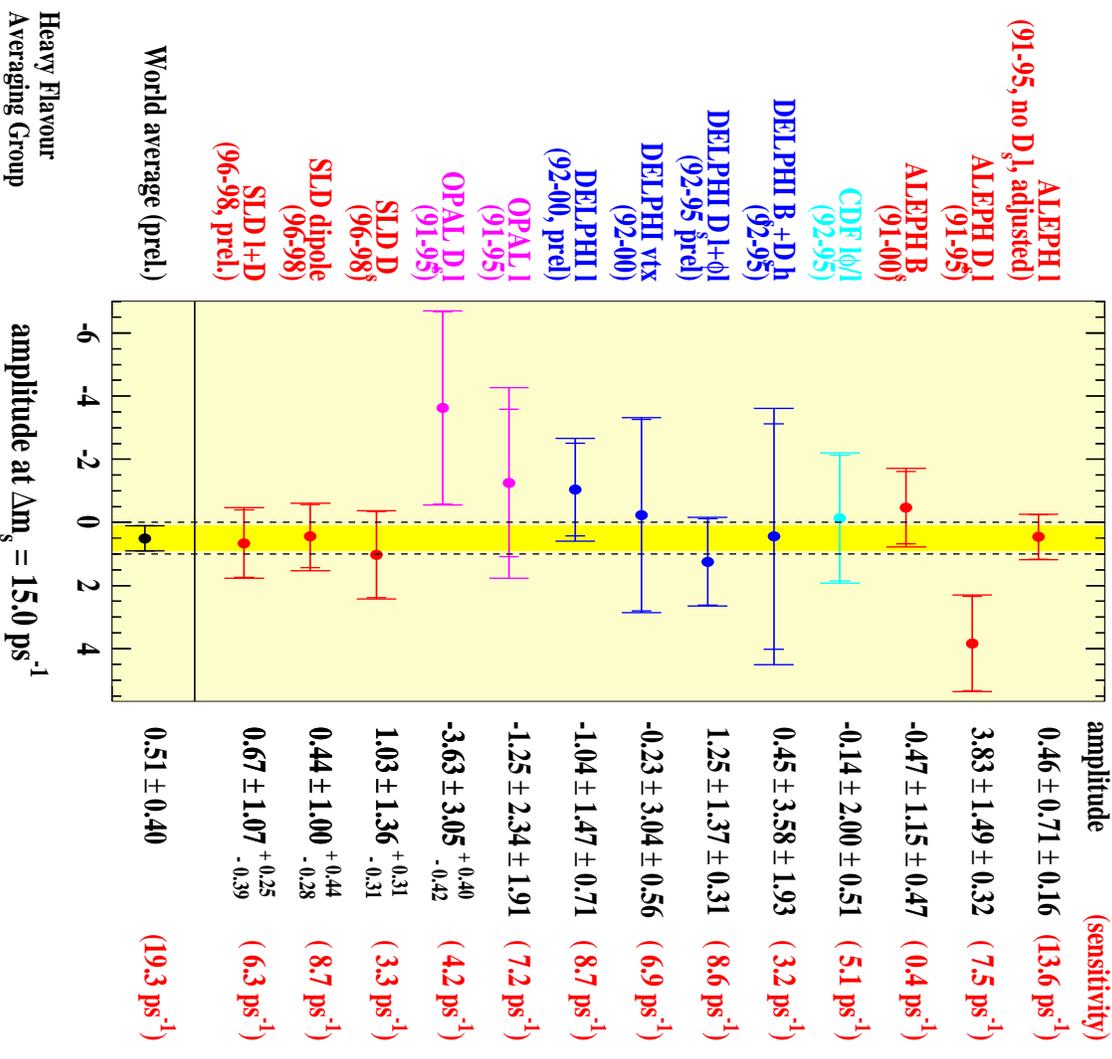
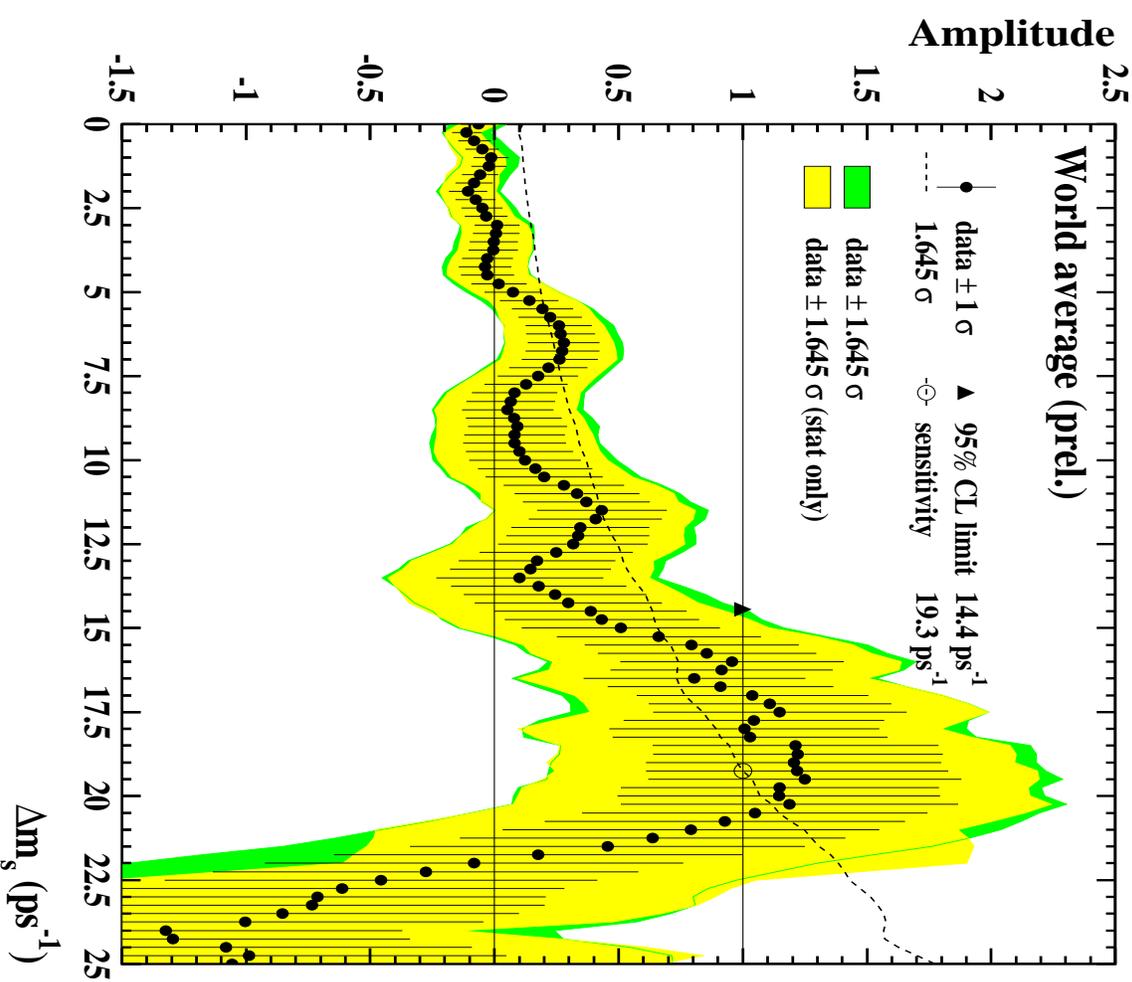
## Current limits on $\Delta m_s$

- Another way to is to **measure  $\mathcal{A}$  for every value of  $\omega$**

$$\mathcal{P}_{u,m}(t) = \frac{\Gamma_s e^{-\Gamma_s t}}{2} [1 \pm \mathcal{A} \cos(\omega t)]$$

- If  $\omega \ll \Delta M_s$ ,  $\mathcal{A}=0$ , while at the true frequency  $\omega = \Delta M_s$ ,  $\mathcal{A}$  expected to be 1
- All values of the test frequency  $\omega$  for which  $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$  were excluded at the **95% CL** ( $\sigma_{\mathcal{A}} \sim 1/S$ )
- Current limit  $\Delta m_s > 14.4 \text{ ps}^{-1}$  (Sensitivity was  $19.3 \text{ ps}^{-1}$ )  
Poorer result due to a “hint” of signal at  $17 \text{ ps}^{-1}$  ( $\approx 2.5\sigma$ )
- If we **remove  $\Delta m_s$  from Unitarity triangle fits** measurements prefer  $\Delta m_s$  around  $15 \pm 4 \text{ ps}^{-1}$
- From UT fits, **Standard Model** upper limit  $\Delta m_s \leq 31 \text{ ps}^{-1}$  at 95% CL

# $B_s \bar{B}_s$ Mixing Results (Winter 2003 conferences)



## Time-integrated mixing measurement

- For these measurements one chooses flavour specific final states
- $\chi_{d(s)}$  is defined as (assuming no CP violation in mixing),

$$\chi = \frac{x^2 + y^2}{2(x^2 + 1)}, \quad x = \frac{\Delta m}{\Gamma}, y = \frac{\Delta \Gamma}{2\Gamma}$$

- ARGUS, CLEO measure  $\chi_d = 0.182 \pm 0.015$
- Combining with  $\Delta m_d$ , get  $\chi_d = 0.181 \pm 0.004$

- From high energy collider experiments,

$$\bar{\chi} = f_d \chi_d + f_s \chi_s = 0.1884 \pm 0.0045$$

- Combining  $\chi_d, \bar{\chi}$  (and assuming  $\chi_s = 1/2$ ) with measured values of  $f_d (\equiv f_u), f_s, f_{\text{baryon}}$  allows us to tighten the errors on the fractions of b hadrons

- With this procedure,
  - $f_d = (38.8 \pm 1.3\%)$  (measd. value =  $(37.3 \pm 2.0)\%$ )
  - $f_s = (10.6 \pm 1.3\%)$  (measd. value =  $(13.9 \pm 3.8)\%$ )
  - $f_{\text{baryon}} = (11.8 \pm 2.0\%)$  (measd. value =  $(11.5 \pm 2.0)\%$ )

## Limits on $\Delta\Gamma/\Gamma$

- CP violation in B mixing is small (mass  $\approx$  CP eigenstates )

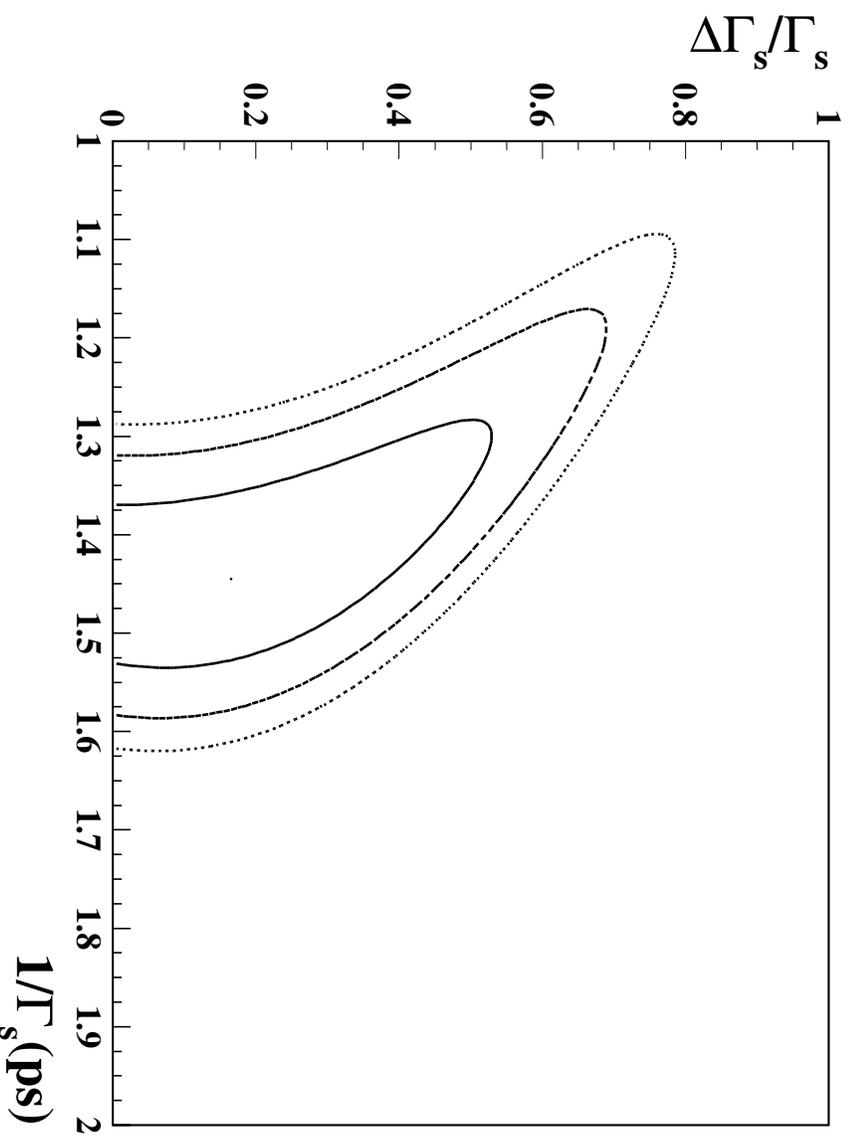
$$\frac{\Delta\Gamma}{\Delta m} \simeq \frac{3\pi}{2} \frac{m_b^2}{m_W^2} \frac{1}{S_0(m_t^2/m_W^2)} \sim \mathcal{O}(0.01)$$

Previous BaBar result can be used to set a limit on  $\Delta\Gamma_d/\Gamma_d$

- $\text{sgn}(\text{Re}\lambda_{CP})\Delta\Gamma/\Gamma = -0.008 \pm 0.037 \pm 0.018$  [-0.084, 0.068]
- $\lambda_{CP}$  characterizes decays like  $B_d \rightarrow$  Charmonium +  $K_{S(L)}^0$

Measure  $\Delta\Gamma_s$  using

- Inclusive  $B_s$  decays which contain both components  
Fit with **single exponential** sensitive to  $(\Delta\Gamma_s/\Gamma_s)^2$
- $J/\Psi\Phi$  - Can separate out CP even and odd states - **Transversity analysis**
- $\mathcal{B}(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})$  is sensitive to  $(\Delta\Gamma_s/\Gamma_s)$



68%, 95% and 99% CL 2D-contours (B WG 2003)

If  $\Gamma_s$  is constrained to  $\Gamma_{B^0}$  [ $\tau(B^0) = 1.537 \pm 0.015$  ps]

$\Delta\Gamma_s/\Gamma_s = 0.07_{-0.07}^{+0.09}$ , 95% C.L. is [0,0.29]

If  $\Delta m_s$  is too large,  $\Delta\Gamma_s$  might be observable

## What's New at the Tevatron

For mixing, we need to tag the flavour of the B at production

$$\epsilon = \frac{N_{\text{correct}} + N_{\text{wrong}}}{N_{\text{correct}} + N_{\text{wrong}} + N_{\text{notag}}} \quad D = \frac{N_{\text{correct}} - N_{\text{wrong}}}{N_{\text{correct}} + N_{\text{wrong}}}$$

- $\epsilon$ ,  $D$  are the efficiency and Dilution
- **Mixing measurements**  $\propto \epsilon D^2$

D0 RunII Preliminary (use  $B^+ \rightarrow J/\Psi K^+$  data sample)

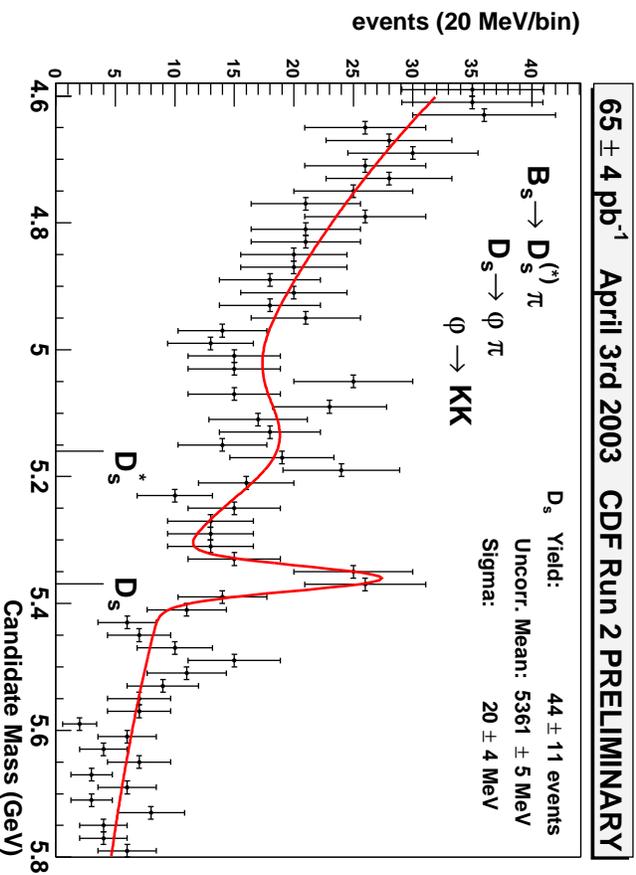
	Jet Tag	Muon Tag
Signal Region: $\epsilon$	$63.0 \pm 3.6\%$	$8.3 \pm 1.9\%*$
Dilution	$15.8 \pm 8.3\%$	$44.4 \pm 21.1\%$
Sideband Region: $\epsilon$	$65.8 \pm 2.4\%$	$8.5 \pm 1.6%*$
Dilution	$2.4 \pm 4.1\%$	$-3.7 \pm 19.2\%$
$\epsilon D^2$ for signal	$2.4 \pm 1.7\%$	$3.3 \pm 1.8\%$

\* **Muon Tag efficiency** includes semi-leptonic branching fraction

Also tag using **Pions and Kaons** from fragmentation (and  $B^{**}$  states)

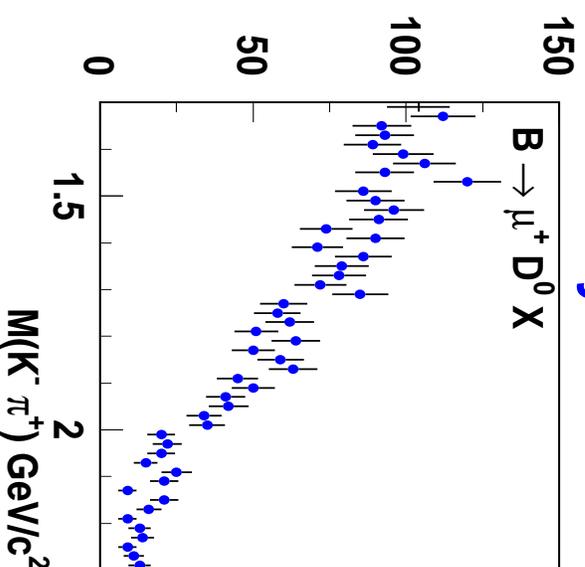
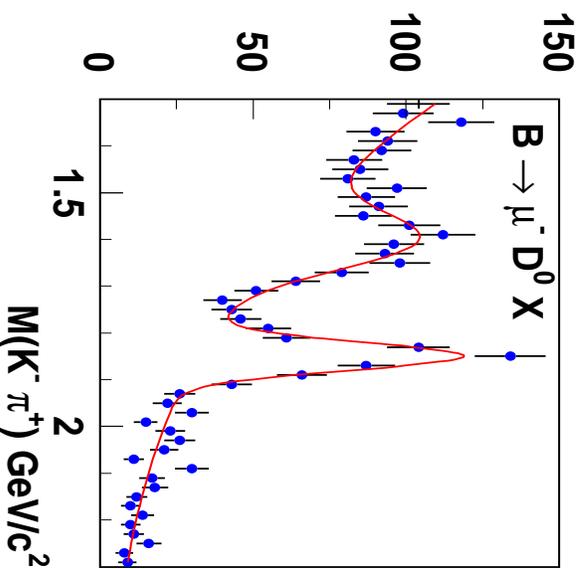
## Final State reconstruction

- $B_s \rightarrow D_s^{(*)}(\eta\pi)$ 
  - Good reconstruction efficiency
  - Good proper time resolution
  - Low branching fractions  $\approx 0.4\%$
- $B_s \rightarrow D_s^{(*)}l\nu$ 
  - Good reconstruction efficiency
  - Poorer proper time resolution
  - Large branching fractions  $\approx 6 - 10\%$



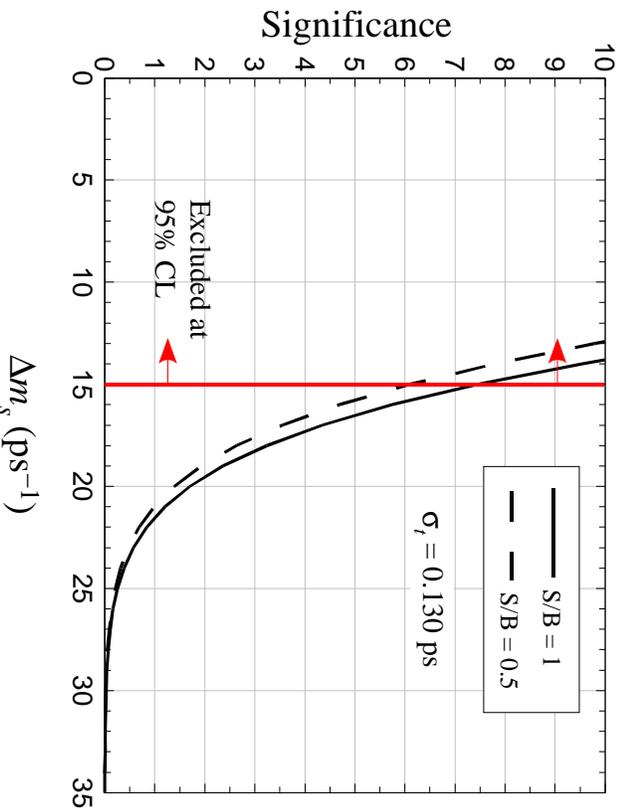
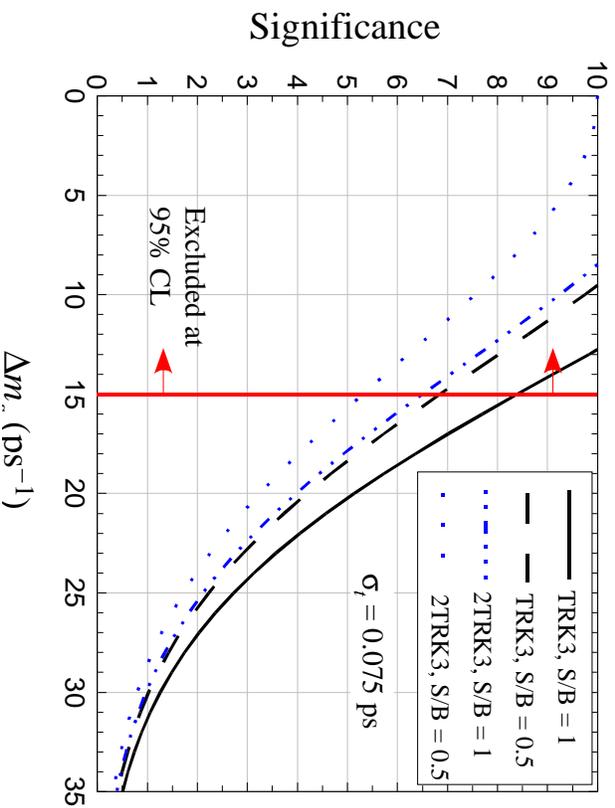
“Golden” mode for mixing

## D0 RunII Preliminary



$$\begin{aligned}
 \mathcal{L} &= 1 \text{ pb}^{-1} \\
 &\approx 450 B \rightarrow D^0 \mu X / \text{pb}^{-1} \\
 &\Rightarrow \approx 40 B_s \rightarrow D_s \mu X / \text{pb}^{-1}
 \end{aligned}$$

## Sample Projections (D0)



$B_s \rightarrow D_s^{(*)} \pi$   
 Reconstruction eff.  $\approx 15\%$   
 Trigger Eff. is  $0.1/0.2\%$  single- $\mu$  triggers  
 Since each event has  $\geq 1$  muon,  $\epsilon D^2$  is high  
 Total Number of reconstructed events:  
 (MC sample): 1300-1900  
 (includes trigger, reco efficiencies, ;  $\mathcal{L} 2 \text{ fb}^{-1}$ )

$B_s \rightarrow D_s^{(*)} \mu \nu$   
 No. events extrapolated from  $B \rightarrow D^0 \mu \nu$  data  
 Assume  $20\text{K}$  on di- $\mu$  trigger  
 Infer proper time resolution from incl.  $B$  lifetime

Re-do with better tracking, Tracker and Silicon Triggers

## Conclusions

- Impressive progress in measuring B-hadron lifetimes,  $\Delta m_d$  at B-factories, LEP and Tevatron experiments
  - $\Delta m_d$  is measured to 1.4%
  - $B^{0(+)}$  lifetimes are known to  $\leq 1\%$
  - $B_s$  lifetime is known to 4%
- CDF and D0 have unique opportunity to extensively study  $B_s$ ,  $B_c$ , B-baryons and measuring  $\Delta m_s$