B Lifetimes and $\mathrm{B\overline{B}}$ Mixing
Results and Prospects
FPCP2003

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(D0 Experiment)

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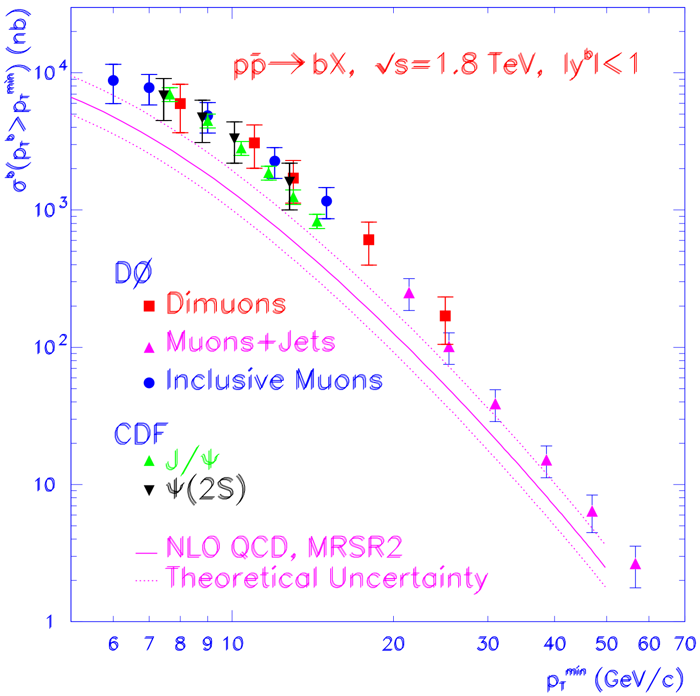
Outline:

- B Lifetimes
- B_d mixing
- B_s mixing
- Conclusions

B physics : Diverse environments



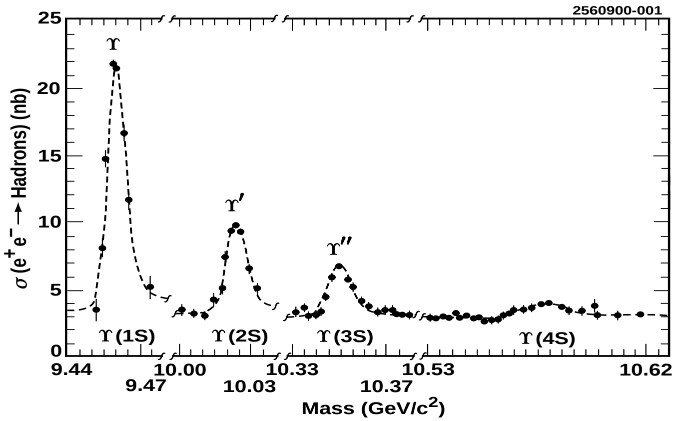
$$\sigma(p\bar{p} \to b\bar{b}) \approx 150\ \mu b \text{ at } \sqrt{s} = 2\text{TeV}$$
$$\sigma(e^+e^- \to b\bar{b}) \approx 7\ nb \text{ at } Z^\circ$$
$$\sigma(e^+e^- \to b\bar{b}) \approx 1\ nb \text{ at } \Upsilon(4S)$$

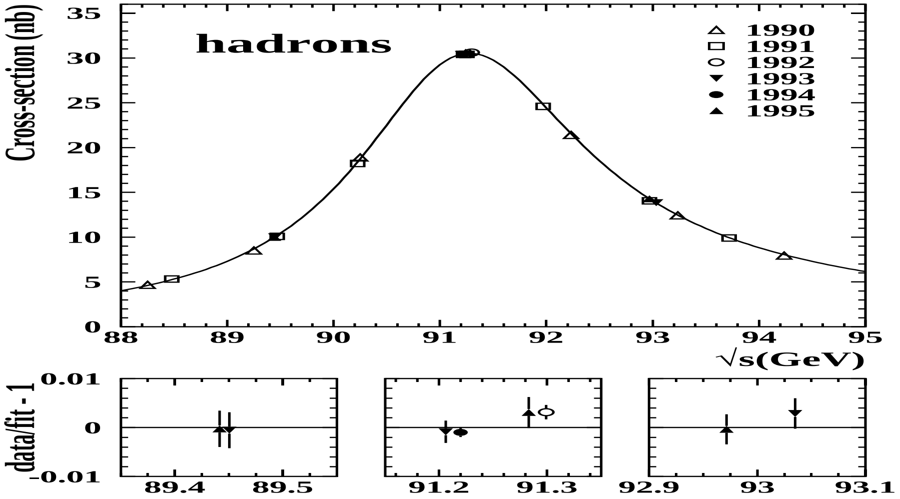
At the Tevatron:

All species produced, including B_s°, B_c, Λ_b

Environment not as clean as e^+e^- machines

Lower trigger efficiencies





CLEO

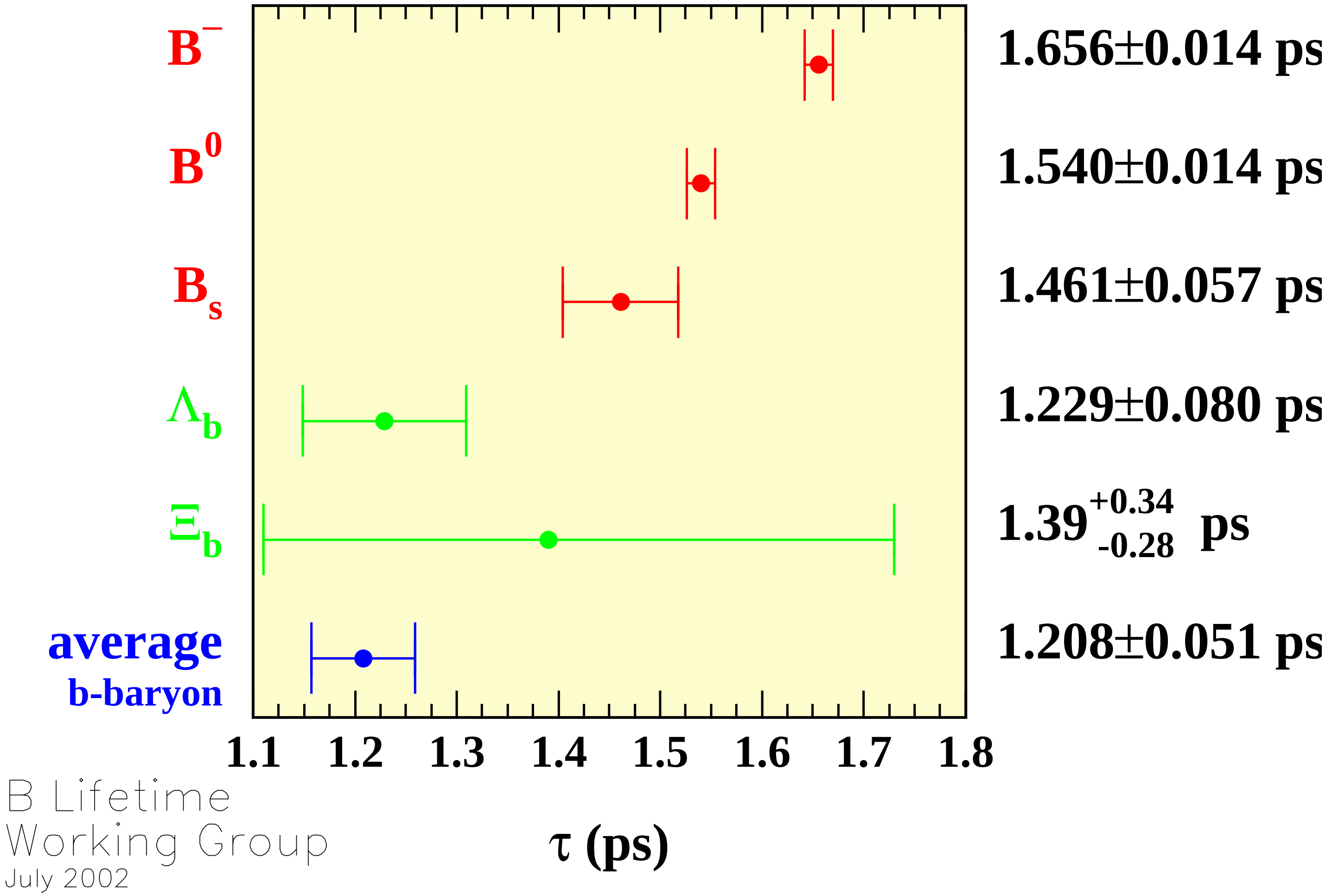
OPAL

Lifetimes

- Lifetime difference between $\mathrm{D}^+, \mathrm{D}^0$ 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 $\approx (1/\mathrm{m}_\mathrm{Q}^2)$ (5% for B hadrons)
- Effects like Pauli Interference, Weak Annihilation arise at $\approx (1/\mathrm{m}_\mathrm{Q}^3)$
  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)
  $\tau(\mathrm{D}^+)/\tau(\mathrm{D}^0) \approx 2$ (PDG: 2.55 ± 0.048) -PI
  $\tau(\mathrm{D}_s)/\tau(\mathrm{D}^0) \approx 0.9 - 1.3$ (PDG: 1.21 ± 0.017) -WA
  $\tau(\Xi_c^+)/\tau(\Lambda_c^+)) \approx 1.3$ (PDG: 2.2 ± 0.20)

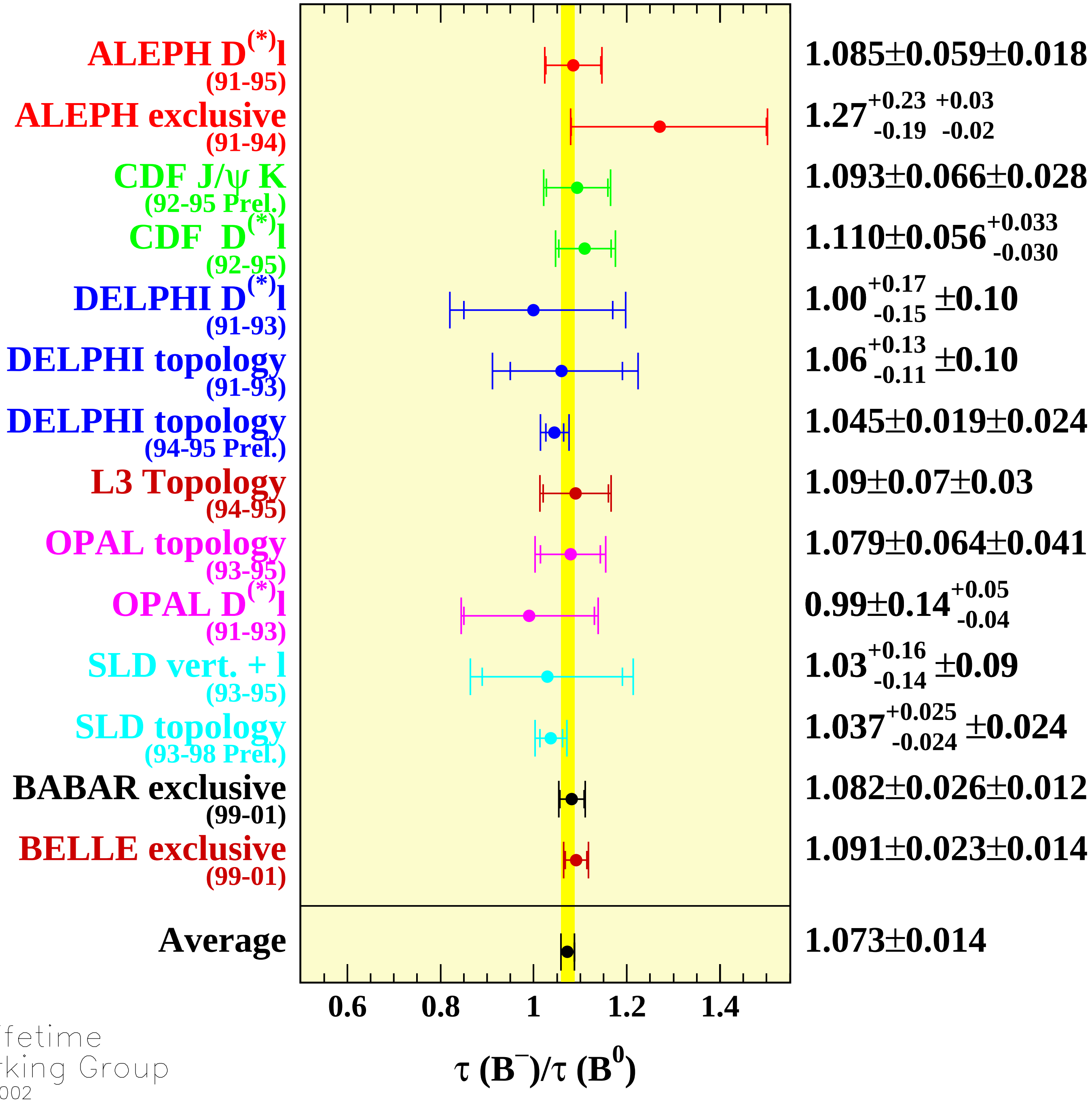
B Lifetimes

- Situation for B hadrons is better, because of larger $\mathrm{m_Q}$
- Most B hadrons have very similar lifetimes
  Using inputs from quenched lattice, NLO prediction:
  $\tau(\mathrm{B}^+)/\tau(\mathrm{B}^0) = 1.053 \pm 0.016 \pm 0.017$
  (unquenching effects could be sizable) - Nierste, hep-ph/0209008
- OPE predicts $\tau(\mathrm{B}_c^+) \approx 0.5$ ps (PDG: 0.46 ± 0.17)
  absence of $\sim \mathcal{O}$ $(1/\mathrm{m_Q})$ corrections is crucial here
- Λ_b is still a "puzzle"
  $\tau(\Lambda_b)/\tau(\mathrm{B}_d^0) \approx 0.9 - 1.0$ (PDG: 0.80 ± 0.05)
- Expectation for $\tau(\mathrm{B}_s)/\tau(\mathrm{B}_d) \approx 1.0 \pm \mathcal{O}(0.01)$
- Need experimental results for other beauty baryons, $e.g.$ Ξ_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)

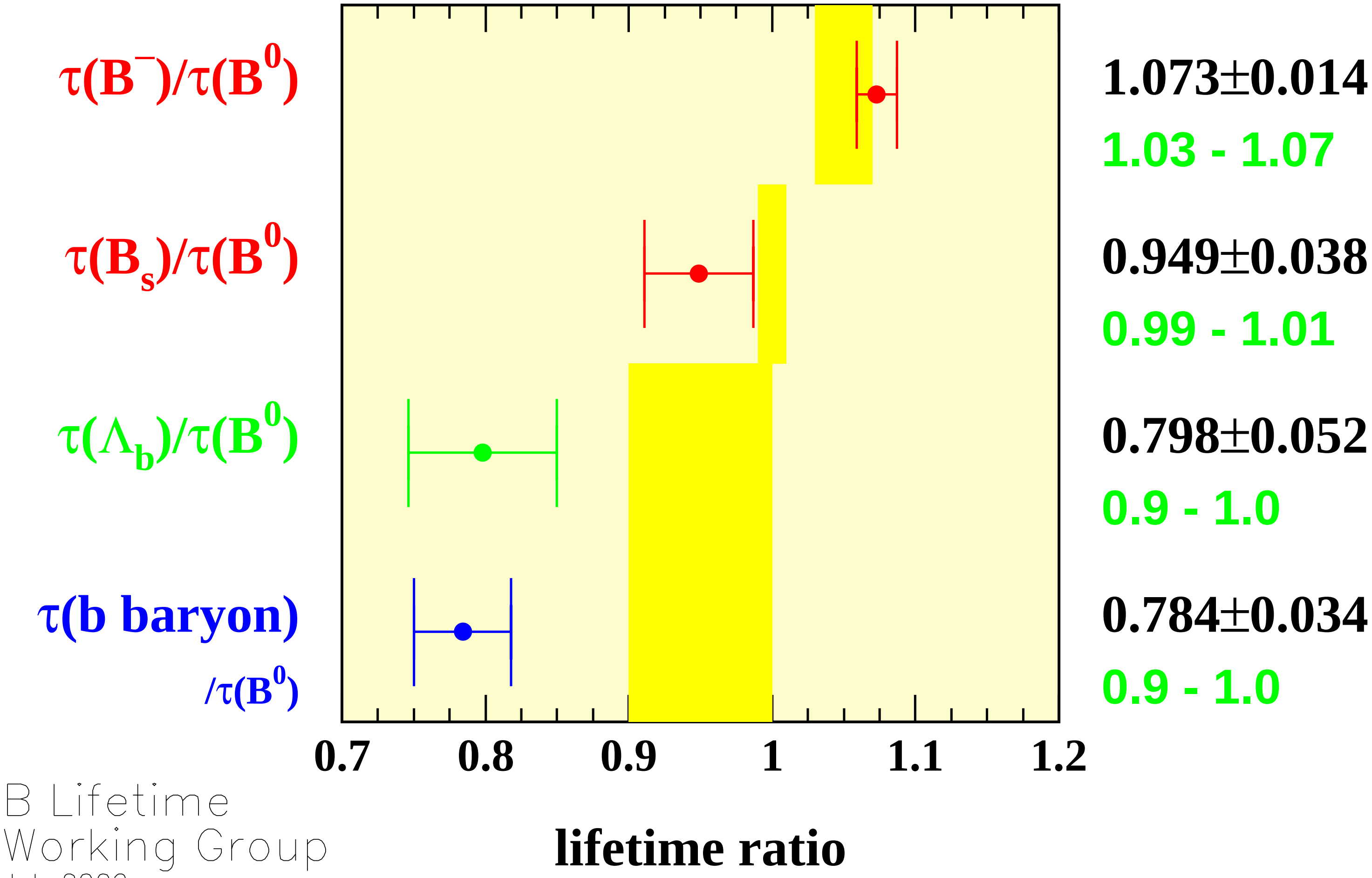


Exclusive and Inclusive measurements for B°, B^+, B_s

Inclusive measurements for Λ_b, Ξ_b, B_c



B Lifetime
Working Group
July 2002



B Lifetime
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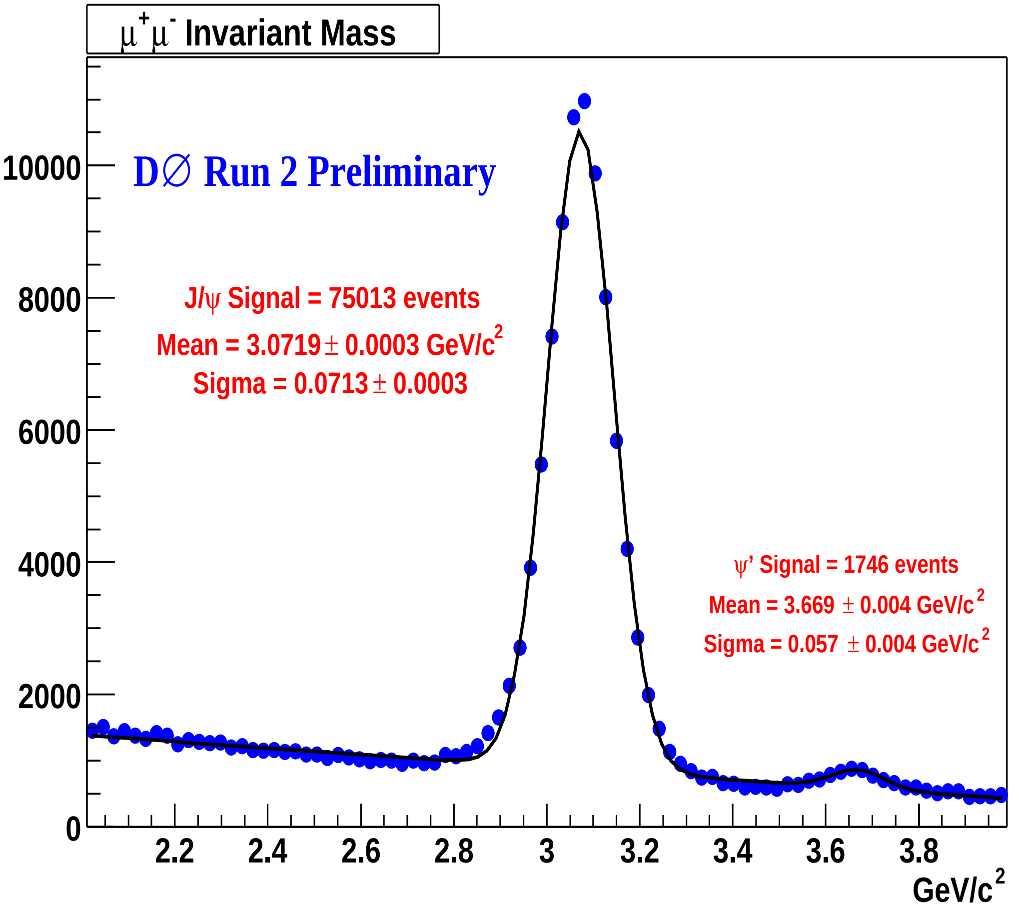
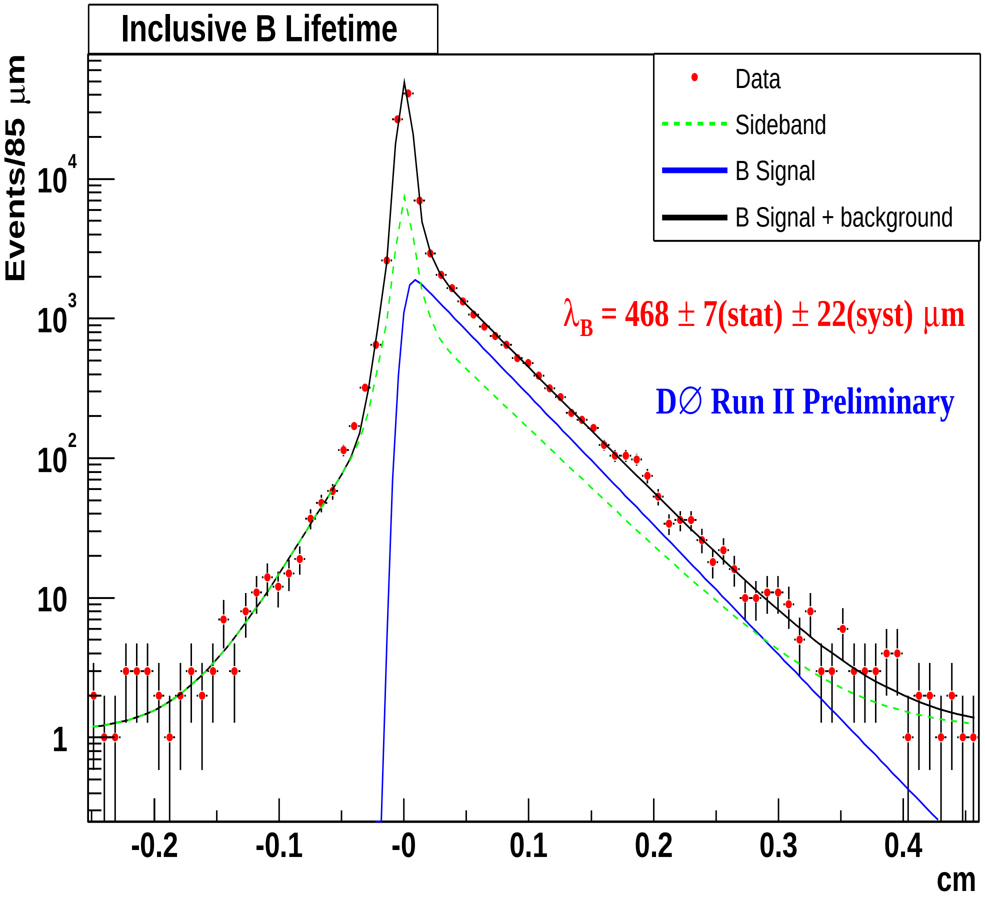
Theory predictions

New Results from the Tevatron

D0 is new to this arena

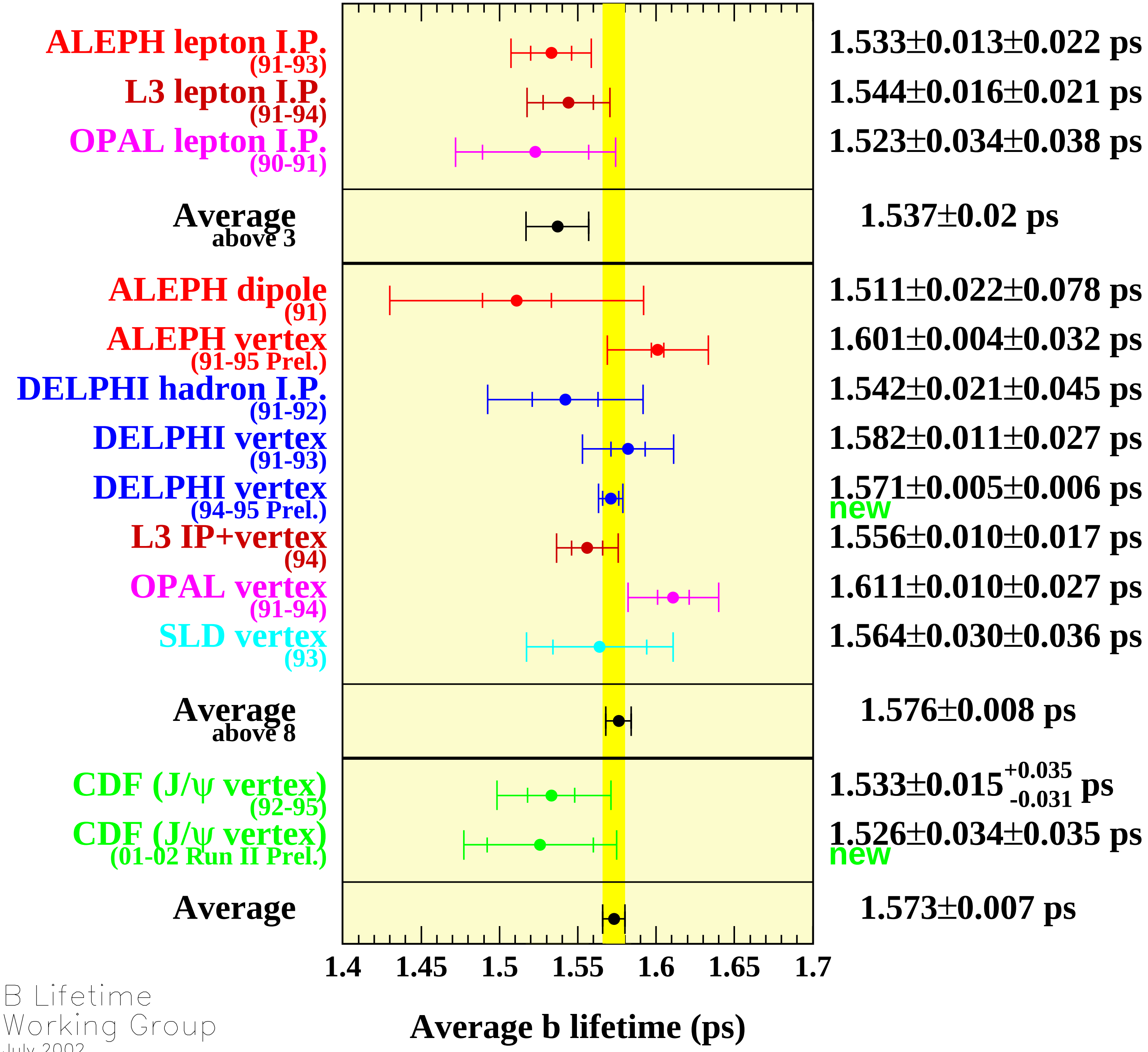
($\mathcal{L} \approx 45\text{pb}^{-1}$)





Correction Factor needed to infer B momentum from J/Ψ vertex

$\langle\tau\rangle = 1.561 \pm 0.024(\mathrm{stat}) \pm 0.074(\mathrm{syst})$ ps (B WG: 1.573 ± 0.007)



B Lifetime
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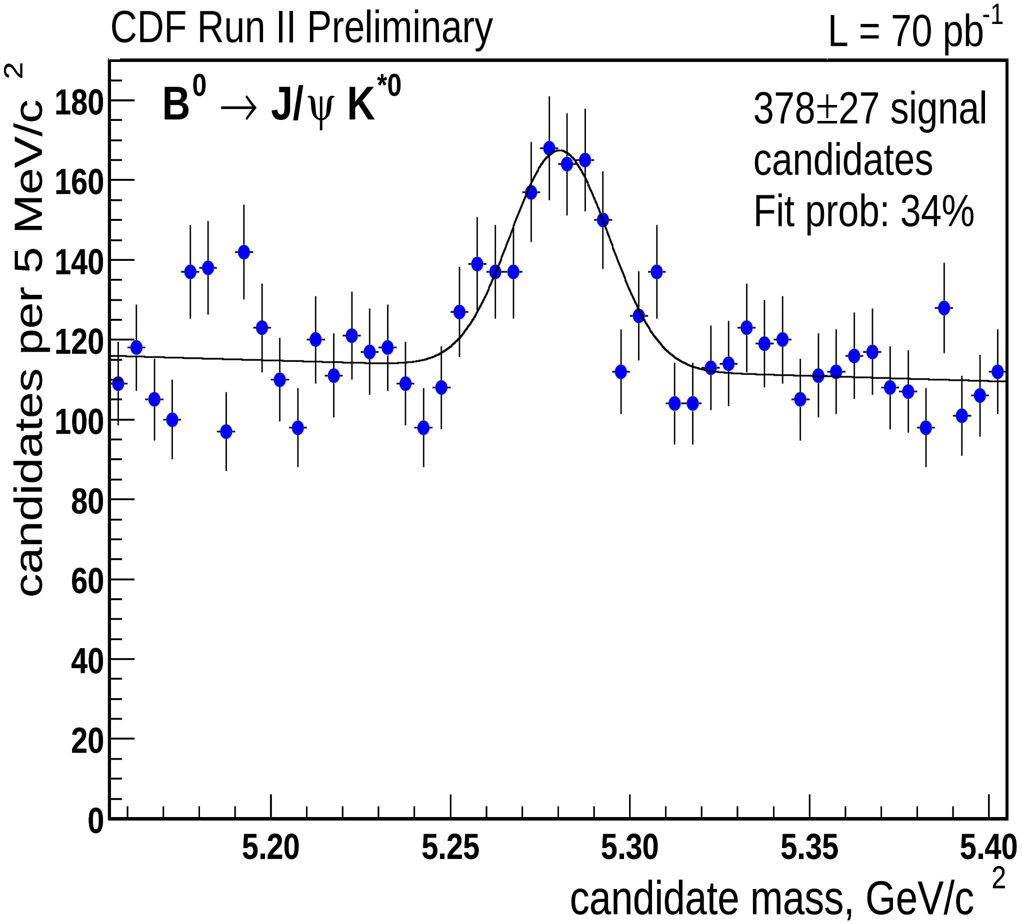
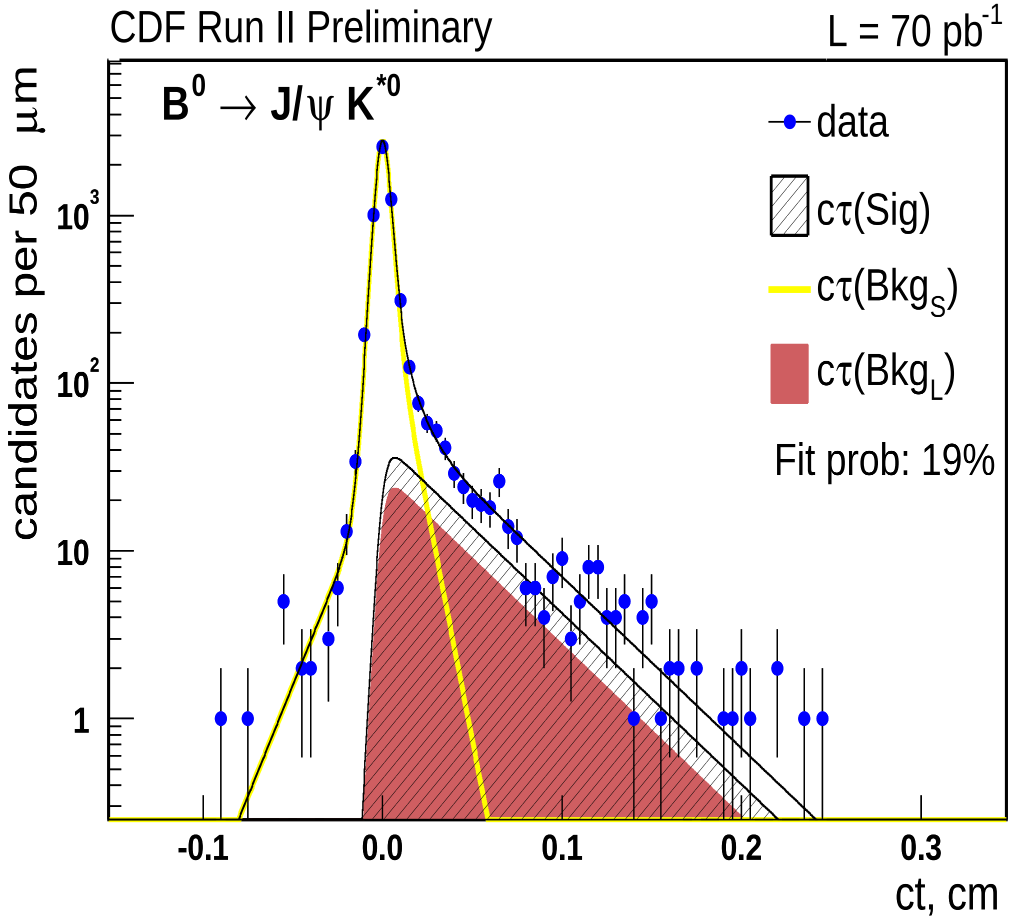
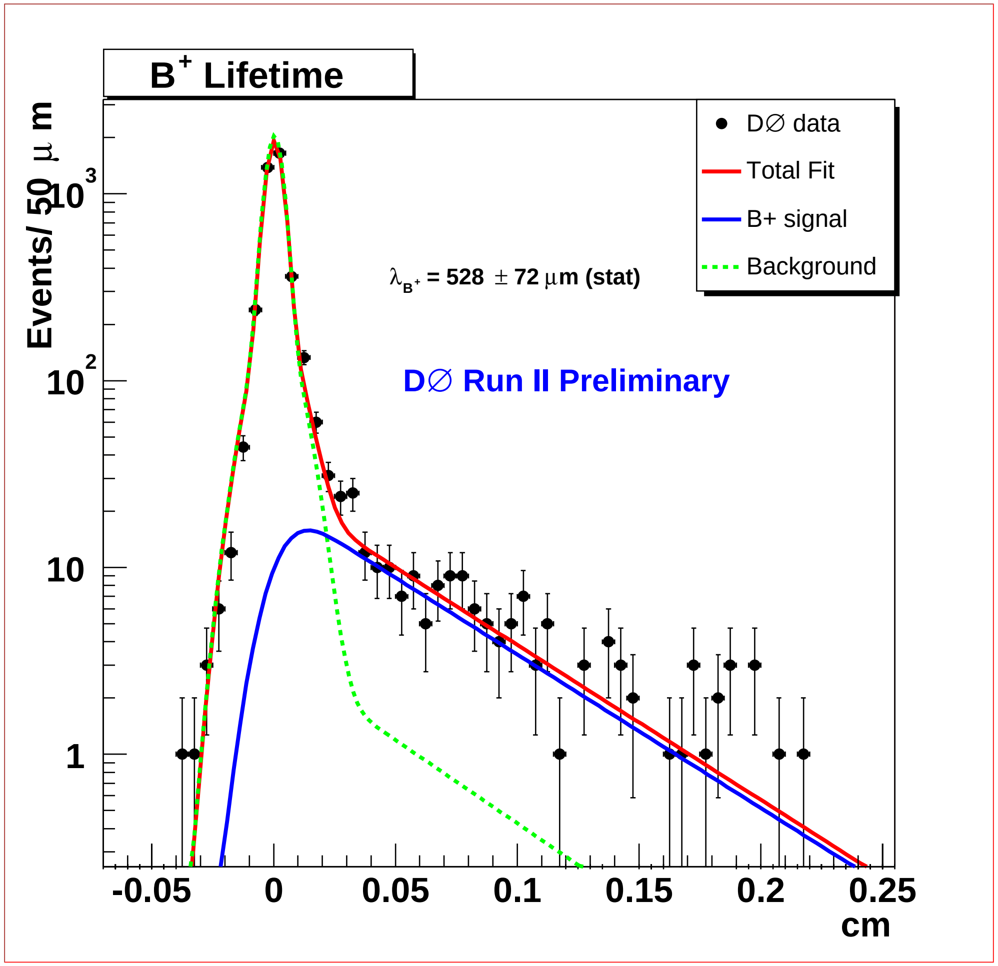




$\langle\tau\rangle = 425 \pm 28 \pm 6\mu\mathrm{m}$ (B WG: $462 \pm 4\mu\mathrm{m}$)

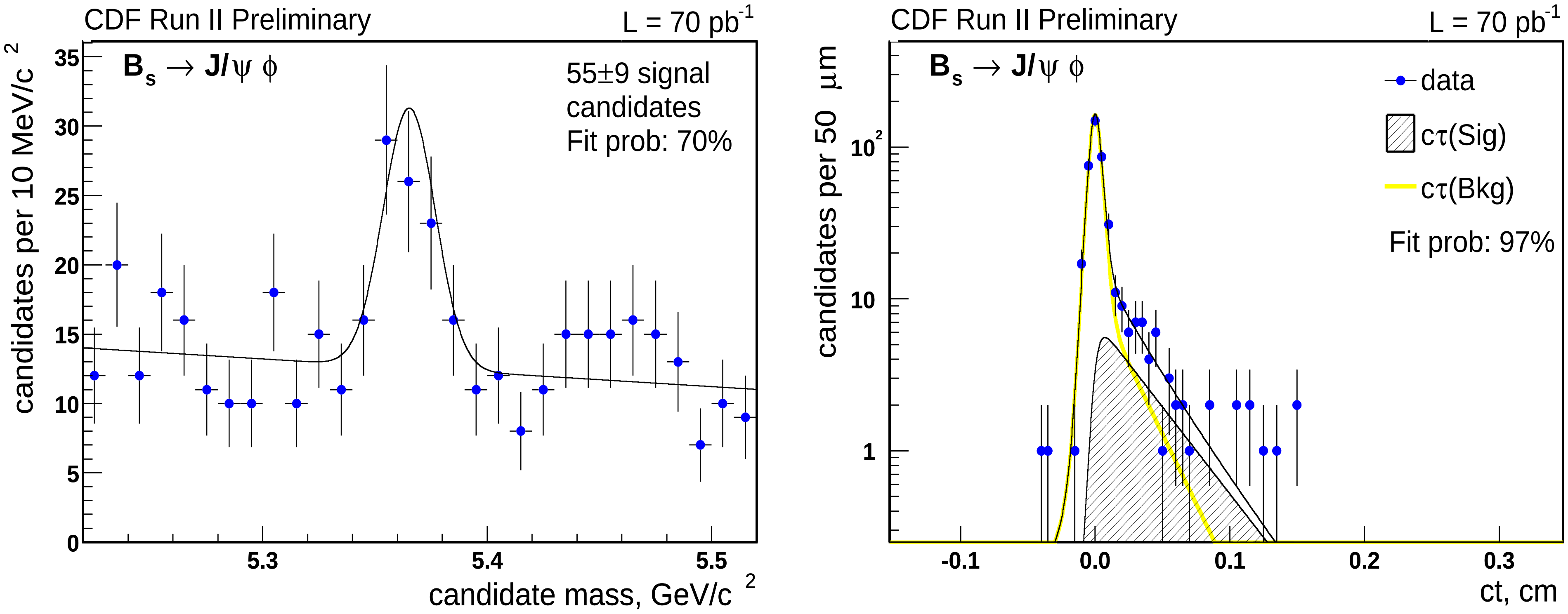
$\lambda_{B^\pm}$ distribution $(\mathcal{L} \approx 45\mathrm{pb}^{-1})$



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

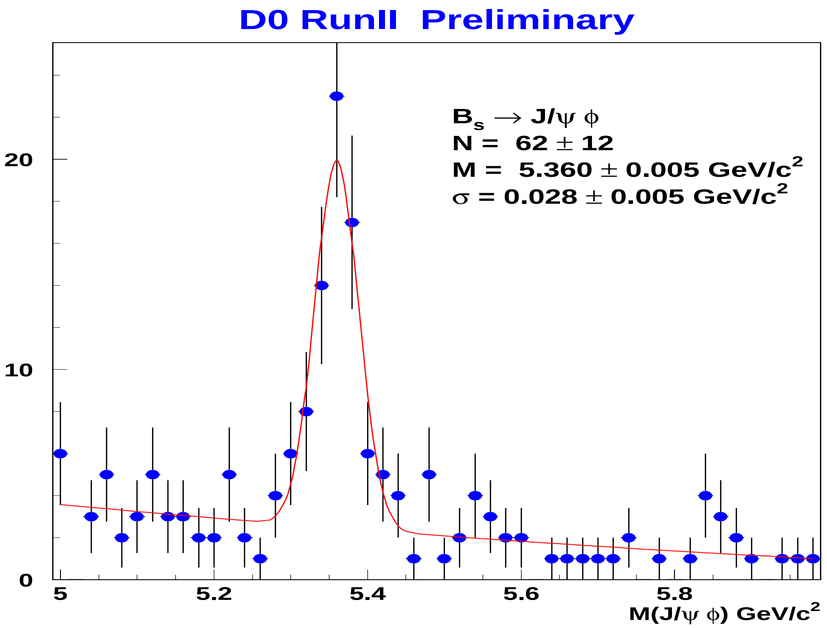
CDF $\langle\tau\rangle = 1.57 \pm 0.07 \pm 0.02$ ps $(\mathcal{L} \sim 70$ pb$^{-1})$

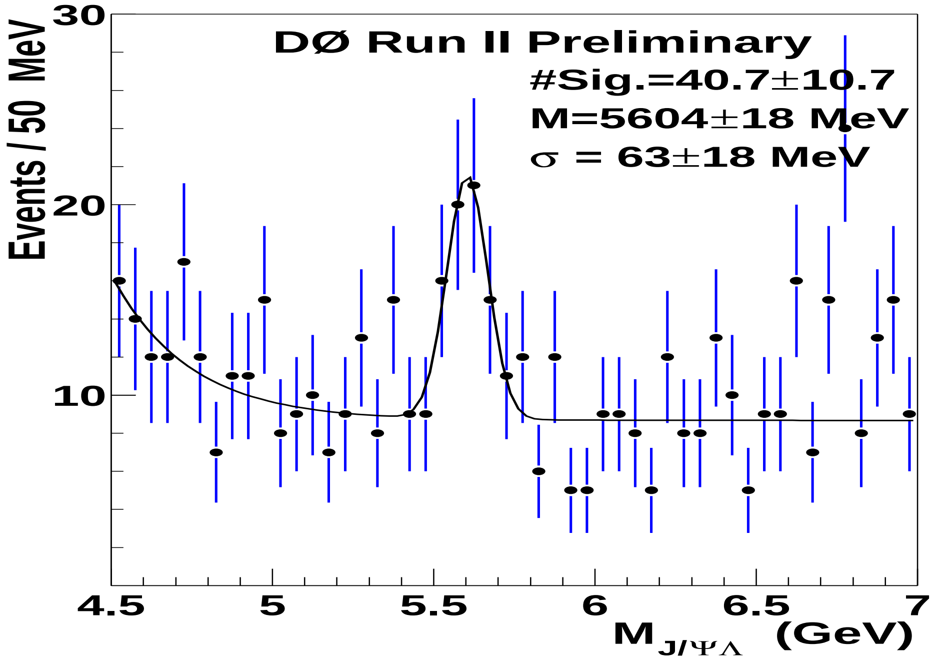
All previous measurements of B_s (except CDF)
and Λ_b lifetimes were with inclusive decays
Both CDF and D0 are fully reconstructing these decays

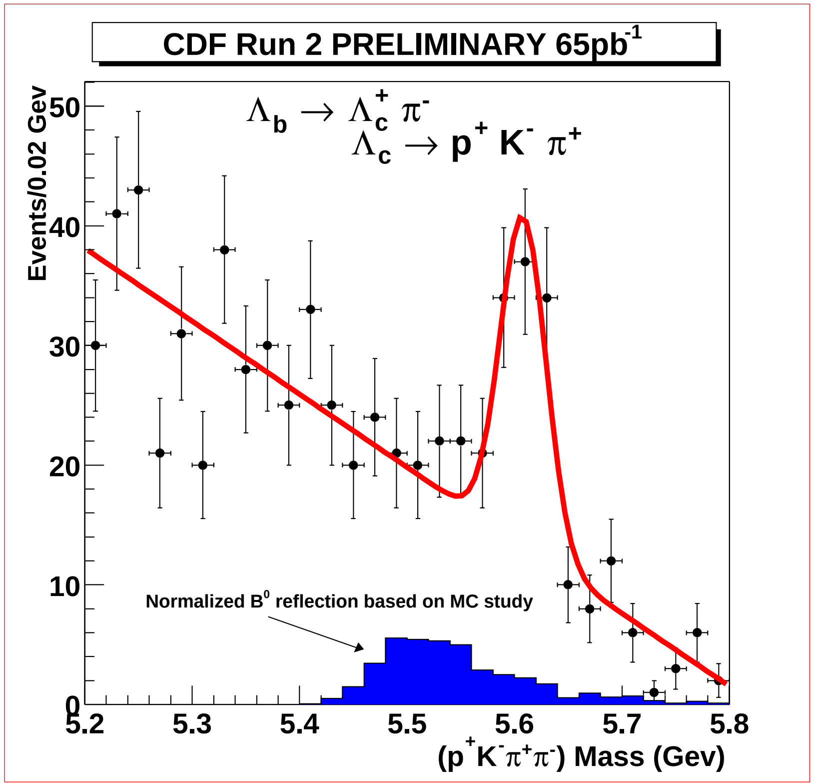


$\langle\tau\rangle = 379 \pm 59 \pm 6\mu\mathrm{m}$ (B WG: $438 \pm 17\mu\mathrm{m}$)

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





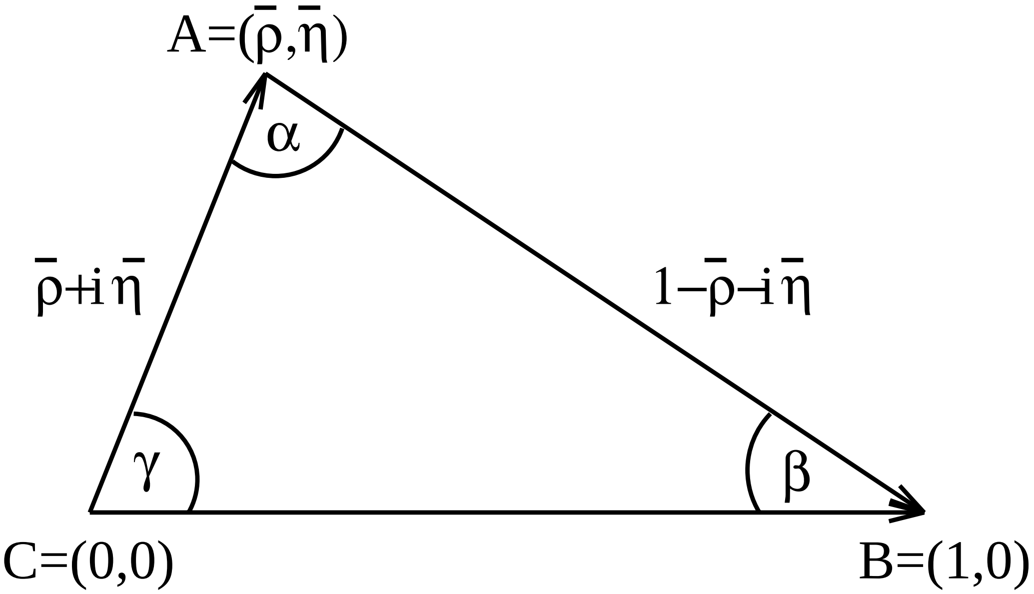


Event estimates for 1 fb^{-1}

$B_s \to J/\Psi\Phi \approx 1000 - 1500$ events
$\Lambda_b \to J/\Psi\Lambda \approx 1000$ events
$\to \Lambda_c\pi \quad \approx 1000$ events
$B_c \to J/\Psi l\nu \approx 300 - 1000$ events
$\to J/\Psi\pi \quad \approx \ 50 - \ 100$ events

Stay tuned for lifetime analyses!

$B\overline{B}$ oscillations

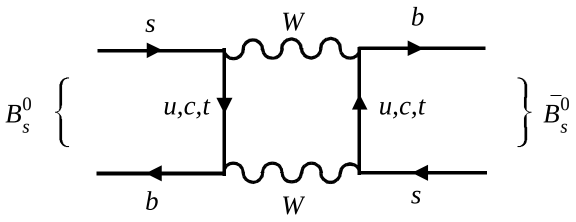


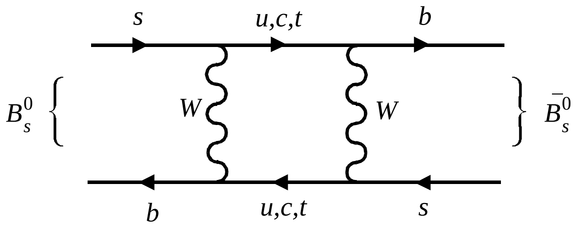
where sides CA and BA are given by R_b, R_t respectively

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

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

R_t can be obtained from B_d, B_s oscillations





Proceeds via second order weak transition

$\mathrm{B}\overline{\mathrm{B}}$ mixing very important in constraining CKM

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

$$\mathrm{R}_t = 0.88 \left[\frac{\xi}{1.18}\right] \sqrt{\frac{18.0/\mathrm{ps}}{\Delta \mathrm{M}_s}} \sqrt{\frac{\Delta \mathrm{M}_d}{0.5/\mathrm{ps}}}, \qquad \xi = \frac{\sqrt{\mathrm{B}_{B_s}}\mathrm{F}_{B_s}}{\sqrt{\mathrm{B}_{B_d}}\mathrm{F}_{B_d}}$$

- Mass eigenstates can be written in terms of flavour eigenstates

$$|\mathrm{B}_s^L\rangle = \mathrm{p}|\mathrm{B}_s^0\rangle + \mathrm{q}|\overline{\mathrm{B}}_s^0\rangle$$
$$|\mathrm{B}_s^H\rangle = \mathrm{p}|\mathrm{B}_s^0\rangle - \mathrm{q}|\overline{\mathrm{B}}_s^0\rangle$$

- $\Delta \mathrm{M}_s \equiv \mathrm{M}_H - \mathrm{M}_L$, $\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H$

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

$$|\mathrm{B}_s^0(\mathrm{t})\rangle = \mathrm{g}_+(\mathrm{t})|\mathrm{B}_\mathrm{s}^0\rangle + \mathrm{g}_-(\mathrm{t})\frac{\mathrm{p}}{\mathrm{q}}|\overline{\mathrm{B}}_\mathrm{s}^0\rangle$$
$$|\overline{\mathrm{B}}_s^0(\mathrm{t})\rangle = \mathrm{g}_-(\mathrm{t})\frac{\mathrm{q}}{\mathrm{p}}|\mathrm{B}_\mathrm{s}^0\rangle + \mathrm{g}_+(\mathrm{t})|\overline{\mathrm{B}}_\mathrm{s}^0\rangle$$

- Unmixed/Mixed probability can be written as

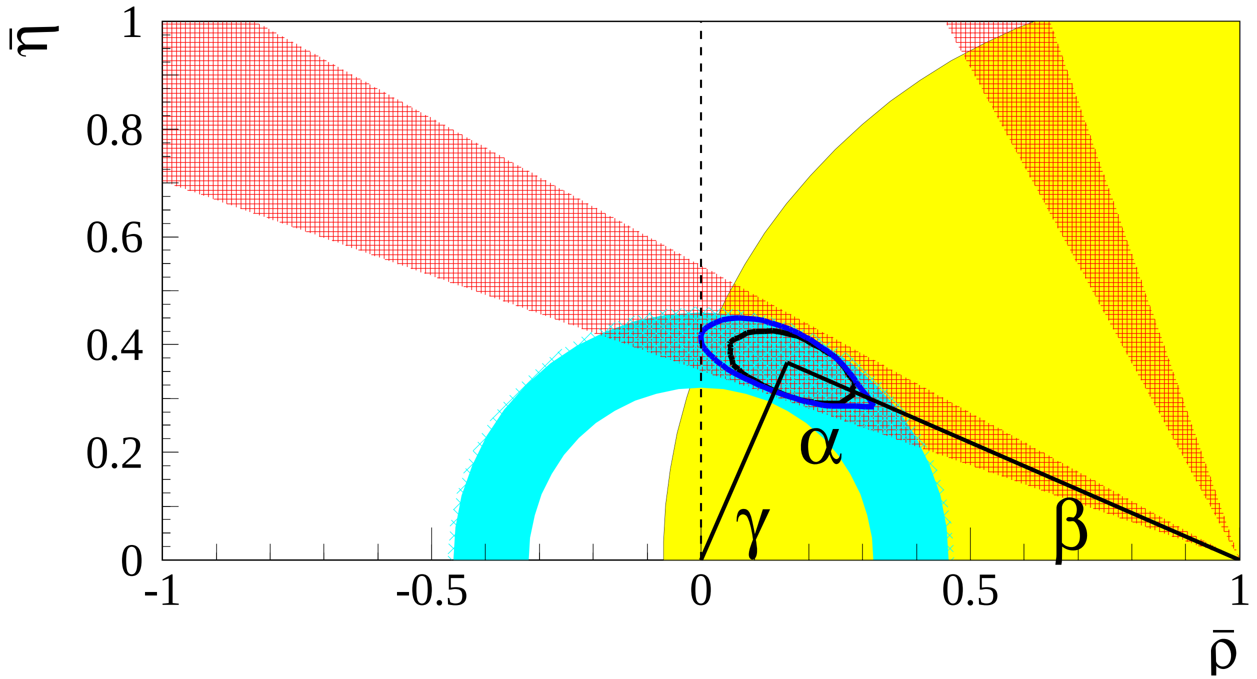
$$\mathcal{P}_{u,m}(\mathrm{t}) = \frac{\Gamma_s \mathrm{e}^{-\Gamma_s \mathrm{t}}}{2}\left[\cosh\left(\frac{\Delta\Gamma_s \mathrm{t}}{2}\right) \pm \cos(\Delta \mathrm{m_s t})\right]$$

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

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

- Can also make time-integrated mixing measurement χ_d (at Υ(4S)) or $\overline{\chi} = \mathrm{f}_d\chi_d + \mathrm{f}_s\chi_s$ (at LEP, Tevatron) where $\chi_{d(s)}$ is a function of $\Delta\mathrm{m}_{d(s)}$,$\Delta\mathrm{m}_{d(s)}$, $\frac{\mathrm{q}}{\mathrm{p}}\frac{\overline{\mathrm{A}}_{\overline{f}}}{\mathrm{A}_f}$

- Study of B hadrons lead to $\eta, V_{ub}/V_{cb}, V_{cb}, V_{td}, V_{ts}$ -
  V_{td}, V_{ts} via $\mathrm{B_d}$, $\mathrm{B_s}$ oscillations
  η can be inferred from CP violation in $\mathrm{B_d} \rightarrow J/\Psi \mathrm{K^0_s}$
- Yellow band is from $\mathrm{B\overline{B}}$ mixing measurements
- $\overline{\rho} > 0$ is from the lower limit on $\mathrm{B_s}$ 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 → J/ΨX, $\mathrm{D}^{(*)}l\nu$, $\mathrm{D}^{(*)}$(nπ),...
- Proper time measurement
- Flavour tagging at production and decay
- Measure asymmetry $\mathcal{A}_f(\mathrm{t})$,

$$\mathcal{A}_f(\mathrm{t}) = \frac{\mathcal{P}_u - \mathcal{P}_m}{\mathcal{P}_u + \mathcal{P}_m} = \frac{\cos(\Delta \mathrm{m_s t})}{\cosh(\frac{\Delta\Gamma_s \mathrm{t}}{2})}$$

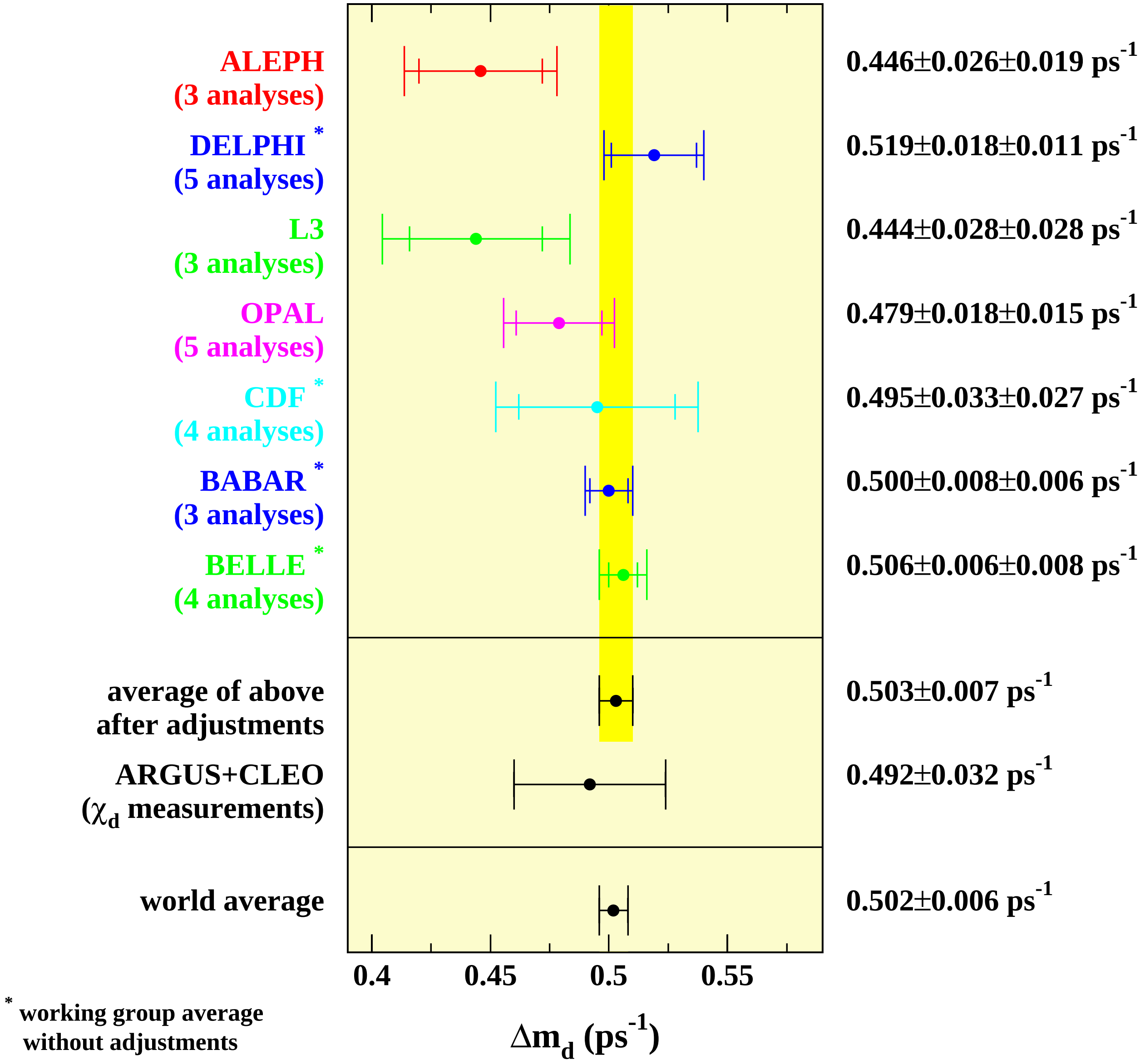
- Crucial component is proper time resolution, t = m_BL/p,

$$\sigma_t = \frac{\mathrm{m}_B}{\mathrm{p}}\sigma_L \oplus \frac{\sigma_p}{\mathrm{p}}\mathrm{t}$$

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

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

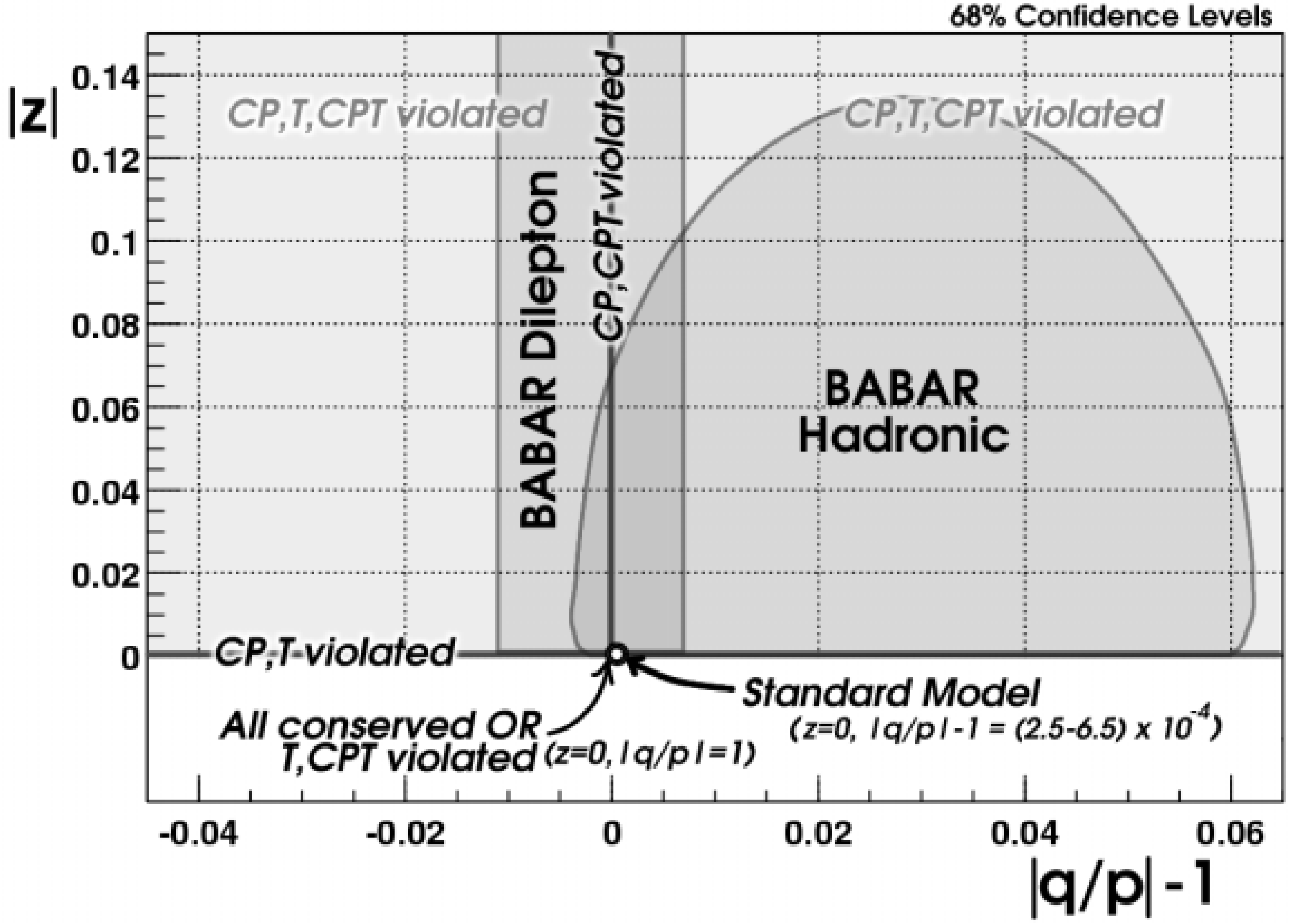
$B_d\overline{B}_d$ Mixing Results (Winter 2003 conferences)



Although Δm_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 $|V_{td}|$

In measurements of $\Delta \mathrm{m}_d$, one generally assumes $\frac{\Delta\Gamma}{\Gamma} = 0$ and no CP, CPT violation

BaBar uses 88 Million $\Upsilon(4S) \rightarrow \mathrm{B}\overline{\mathrm{B}}$ events to search for these effects



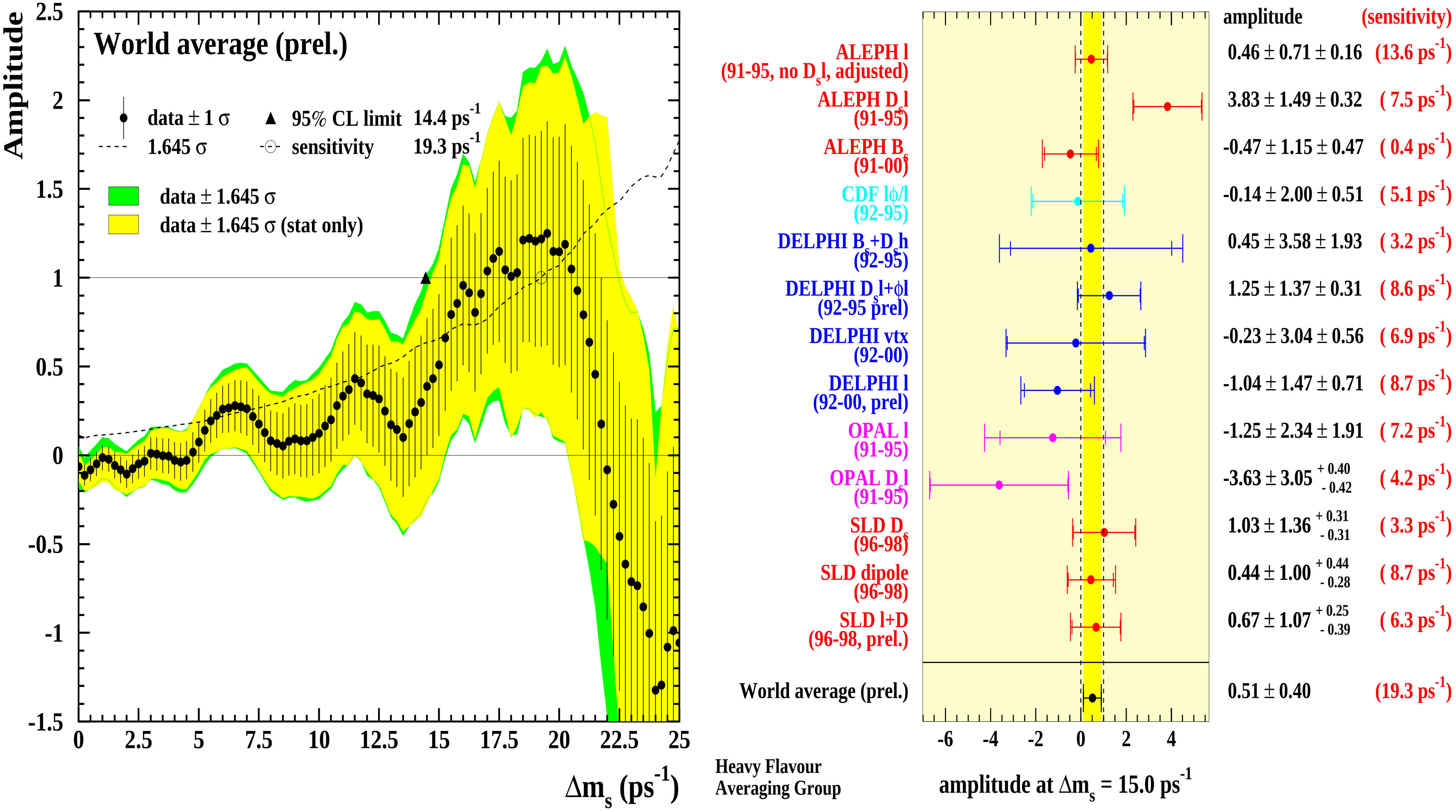
Current limits on $\Delta \mathrm{m}_s$

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

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

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

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



	amplitude	(sensitivity)
ALEPH l (91-95, no D_sl, adjusted)	0.46 ± 0.71 ± 0.16	(13.6 ps^{-1})
ALEPH D_s l (91-95)	3.83 ± 1.49 ± 0.32	(7.5 ps^{-1})
ALEPH B_s (91-00)	-0.47 ± 1.15 ± 0.47	(0.4 ps^{-1})
CDF lφ/l (92-95)	-0.14 ± 2.00 ± 0.51	(5.1 ps^{-1})
DELPHI B_s+D_sh (92-95)	0.45 ± 3.58 ± 1.93	(3.2 ps^{-1})
DELPHI D_sl+φl (92-95 prel)	1.25 ± 1.37 ± 0.31	(8.6 ps^{-1})
DELPHI vtx (92-00)	-0.23 ± 3.04 ± 0.56	(6.9 ps^{-1})
DELPHI l (92-00, prel)	-1.04 ± 1.47 ± 0.71	(8.7 ps^{-1})
OPAL l (91-95)	-1.25 ± 2.34 ± 1.91	(7.2 ps^{-1})
OPAL D_s l (91-95)	-3.63 ± 3.05 $^{+0.40}_{-0.42}$	(4.2 ps^{-1})
SLD D_s (96-98)	1.03 ± 1.36 $^{+0.31}_{-0.31}$	(3.3 ps^{-1})
SLD dipole (96-98)	0.44 ± 1.00 $^{+0.44}_{-0.28}$	(8.7 ps^{-1})
SLD l+D (96-98, prel.)	0.67 ± 1.07 $^{+0.25}_{-0.39}$	(6.3 ps^{-1})
World average (prel.)	0.51 ± 0.40	(19.3 ps^{-1})

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),

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

- ARGUS, CLEO measure $\chi_d = 0.182 \pm 0.015$
- Combining with $\Delta \mathrm{m_d}$, get $\chi_d = 0.181 \pm 0.004$
- From high energy collider experiments,
  $\overline{\chi} = \mathrm{f}_d\chi_d + \mathrm{f}_s\chi_s = 0.1884 \pm 0.0045$
- Combining $\chi_d, \overline{\chi}$ (and assuming $\chi_s = 1/2$)
  with measured values of f_d ($\equiv \mathrm{f}_u$),f_s,$\mathsf{f}_{\mathrm{baryon}}$
  allows us to tighten the errors on the fractions of b hadrons
- With this procedure,
  $\mathsf{f}_d = (38.8 \pm 1.3\%)$ (measd. value $= (37.3 \pm 2.0)\%$)
  $\mathsf{f}_s = (10.6 \pm 1.3\%)$ (measd. value $= (13.9 \pm 3.8)\%$)
  $\mathsf{f}_{\mathrm{baryon}} = (11.8 \pm 2.0\%)$ (measd. value $= (11.5 \pm 2.0)\%$)

Limits on $\Delta\Gamma/\Gamma$

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

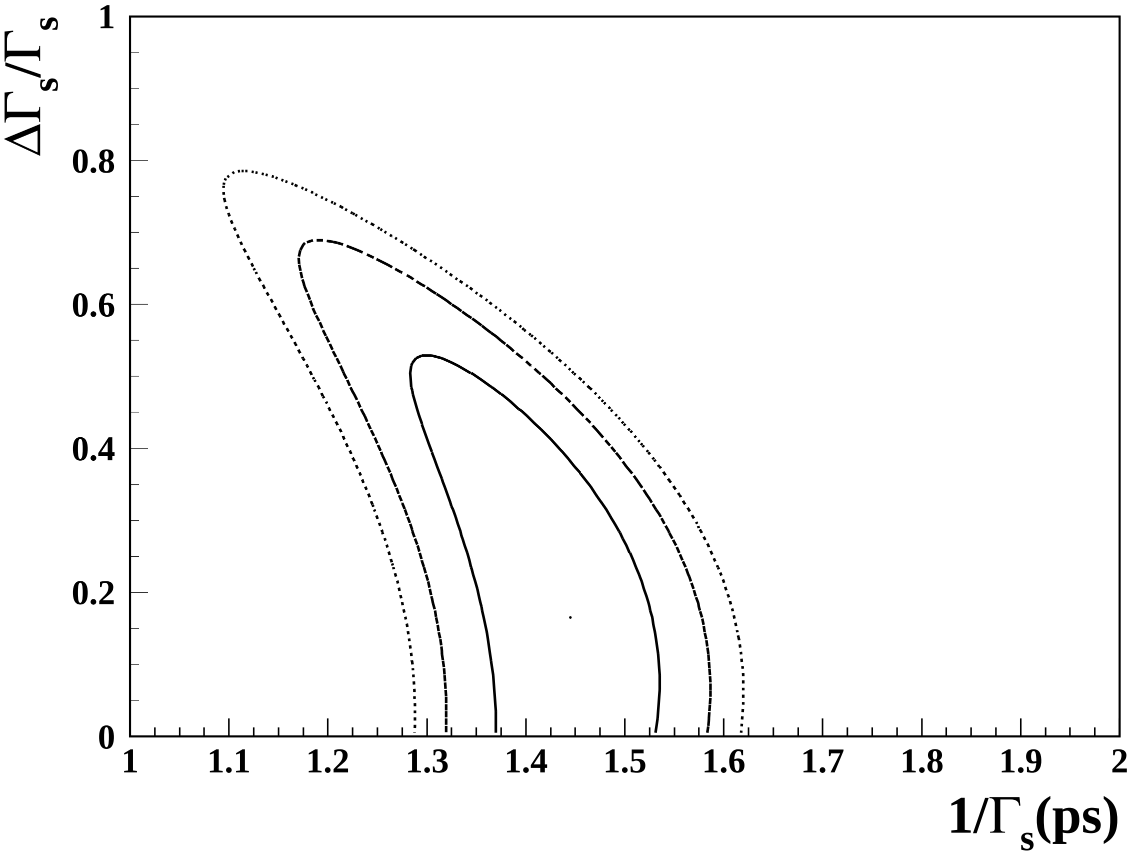
$$\frac{\Delta\Gamma}{\Delta m} \simeq \frac{3\pi}{2}\frac{m_b^2}{m_W^2}\frac{1}{S_0(m_t^2/m_W^2)} \sim \mathcal{O}(0.01)$$

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

- sgn(Reλ_{CP})$\Delta\Gamma/\Gamma = -0.008 \pm 0.037 \pm 0.018$ [-0.084,0.068]
- λ_{CP} characterizes decays like B$_d \rightarrow \mathrm{Charmonium} + \mathrm{K}^{\circ}_{S(L)}$

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 Γ_s is constrained to Γ_{B^0} $[\tau(B^0) = 1.537 \pm 0.015$ ps]
$\Delta\Gamma_s/\Gamma_s = 0.07^{+0.09}_{-0.07}$, 95% C.L. is [0,0.29]

If Δm_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

$$\epsilon = \frac{\mathrm{N_{correct}} + \mathrm{N_{wrong}}}{\mathrm{N_{correct}} + \mathrm{N_{wrong}} + \mathrm{N_{notag}}} \qquad \mathrm{D} = \frac{\mathrm{N_{correct}} - \mathrm{N_{wrong}}}{\mathrm{N_{correct}} + \mathrm{N_{wrong}}}$$

- ϵ , D are the efficiency and Dilution
- Mixing measurements $\propto$ $\epsilon \mathrm{D}^2$

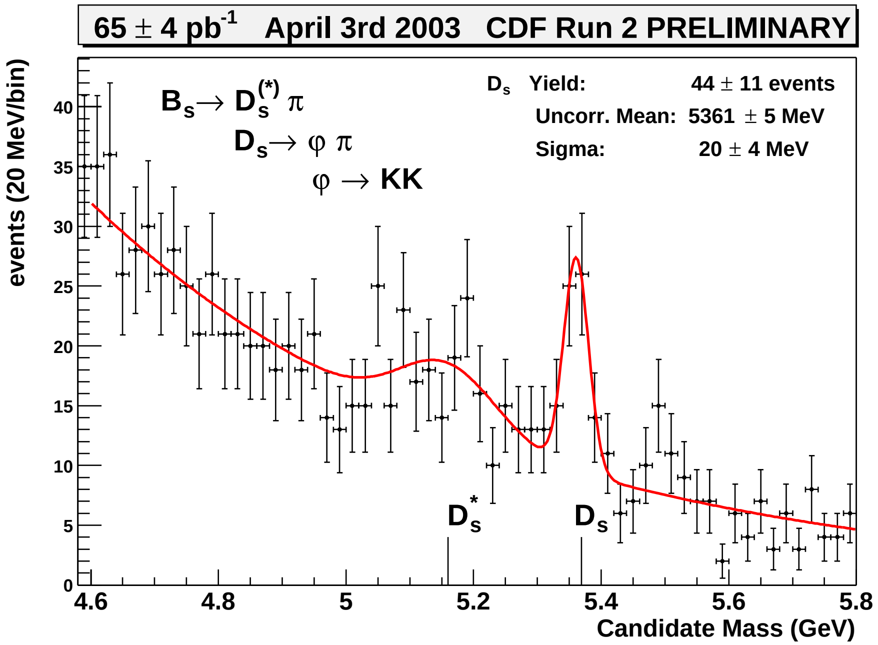
D0 RunII Preliminary (use $\mathrm{B}^+ \to \mathrm{J}/\Psi \mathrm{K}^+$ data sample)

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

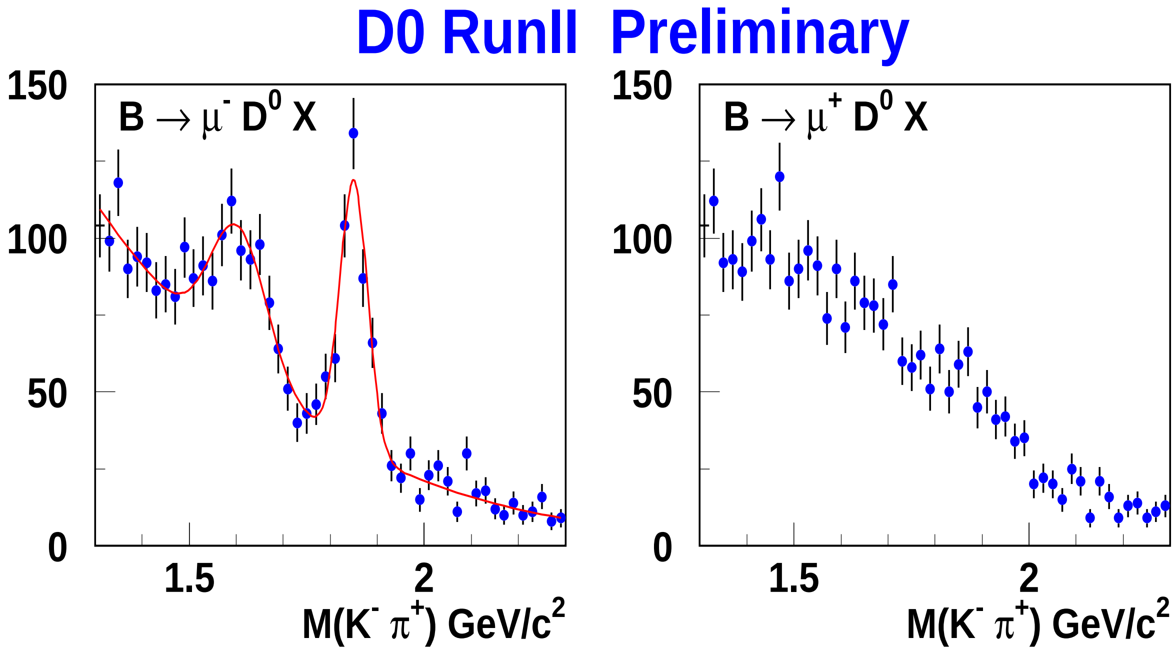
* Muon Tag efficiency includes semi-leptonic branching fraction
Also tag using Pions and Kaons from fragmentation (and B^{**} states)

Final State reconstruction

- $\mathsf{B}_s \to \mathrm{D}_s^{(*)}(\mathrm{n}\pi)$
  - Good reconstruction efficiency
  - Good proper time resolution
  - Low branching fractions $\approx 0.4\%$
- $\mathsf{B}_s \to \mathrm{D}_s^{(*)}\mathrm{l}\nu$
  - Good reconstruction efficiency
  - Poorer proper time resolution
  - Large branching fractions $\approx 6 - 10\%$



"Golden" mode for mixing

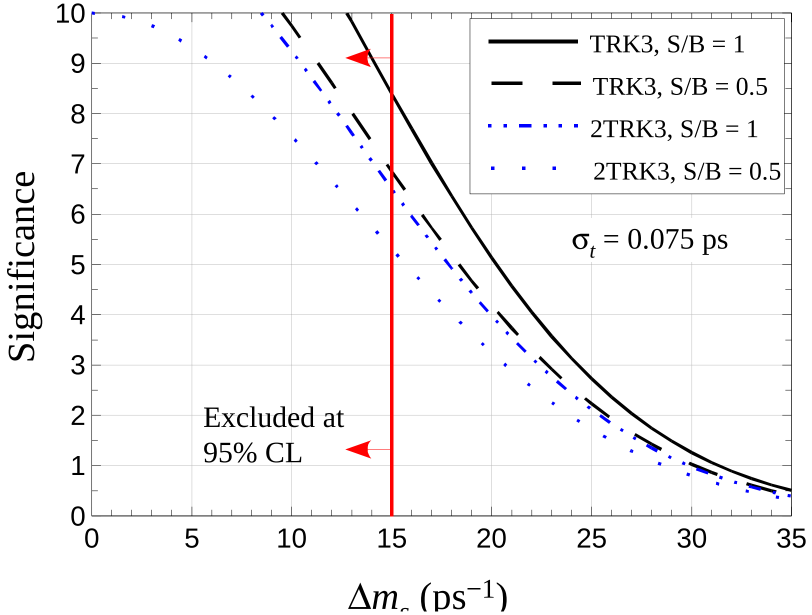


$\mathcal{L} = 1\mathrm{pb}^{-1}$

$\approx 450\ \mathrm{B} \to \mathrm{D}^0\mu\mathrm{X}/\mathsf{pb}^{-1}$

$\Rightarrow\ \approx\ 40\ \mathrm{B}_s \to \mathrm{D}_s\mu\mathrm{X}/\mathsf{pb}^{-1}$

Sample Projections (D0)



$B_s \rightarrow D_s^{(*)}\pi$

Reconstruction eff. $\approx 15\%$

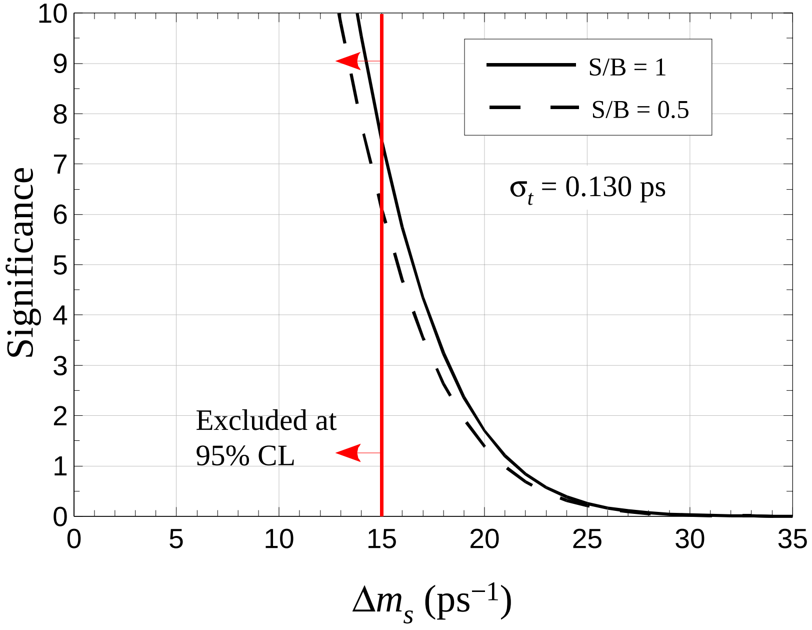
Trigger Eff. is 0.1/0.2% single-μ triggers

Since each event has ≥ 1 muon, ϵD^2 is high

Total Number of reconstructed events:

(MC sample): 1300-1900

(includes trigger, reco efficiencies, ; $\mathcal{L}$ 2 fb^{-1})



$B_s \rightarrow D_s^{(*)}\mu\nu$

No. events extrapolated from B$\rightarrow D^0\mu\nu$ data

Assume 20K on di-μ 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, Δm_d at B-factories, LEP and Tevatron experiments
  - Δm_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 Δm_s