Measurement of the B_s^0 Lifetime and a Measurement of the Lifetime Difference in the B_s^0 System at DØ

For the DØ Collaboration

The Focus of B Physics Studies: CKM Matrix

Relates quark mass and weak eigenstates

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{bmatrix}.$$

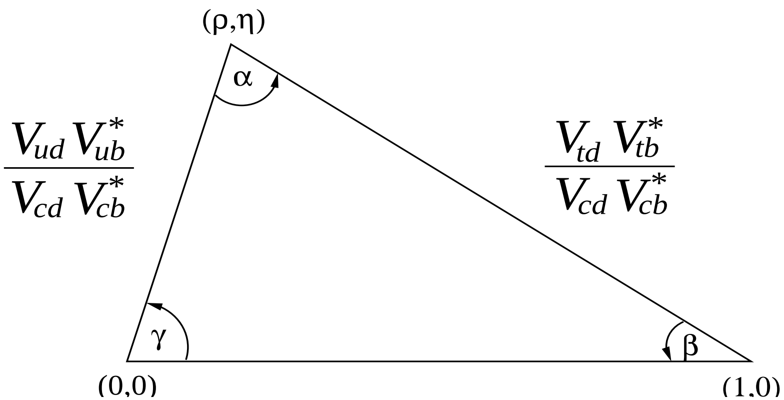
SM: CP-violating processes solely related to one phase in CKM

'bd'

(THE unitary triangle)

Large effort in B physics

Mainly at B factories



'bs'

(A 'squashed' unitary triangle)

$\beta \rightarrow \beta_s$

β_s **small in SM**

Checking if β_s is small is as important as measuring the sides and angles of THE unitary triangle

B_s System

Schrodinger Equation:

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

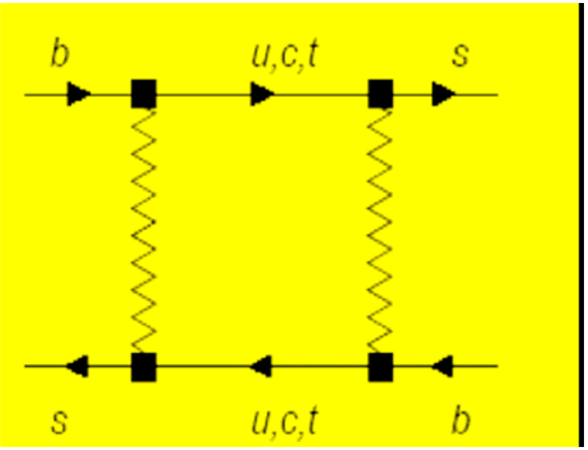
M_{12} stems from the real part of the box diagram, dominated by top

Γ_{12} stems from the imaginary part, dominated by charm

Two physical states, Heavy and Light B_s eigenstates, are expected to have different widths (propagate with different lifetimes)

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

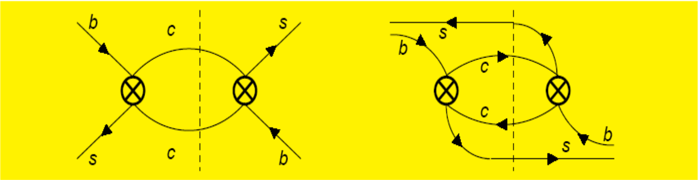
$$B_H = p|B_s\rangle - q|\overline{B}_s\rangle \approx cp\ even\,, \quad p^2 + q^2 = 1$$



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

$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$$

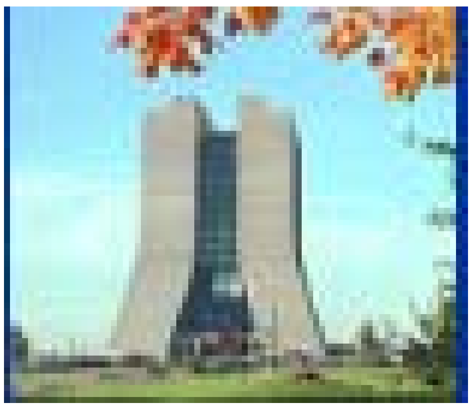
Γ_{12} stems from final states common to B_s and $\overline{B}_s$.



Crosses: Effective $|\Delta B| = 1$ operators from W-exchange.

Γ_{12} is a CKM-favored tree-level effect associated with final states containing a $(\overline{c}, c)$ pair.

Fermilab and the Tevatron

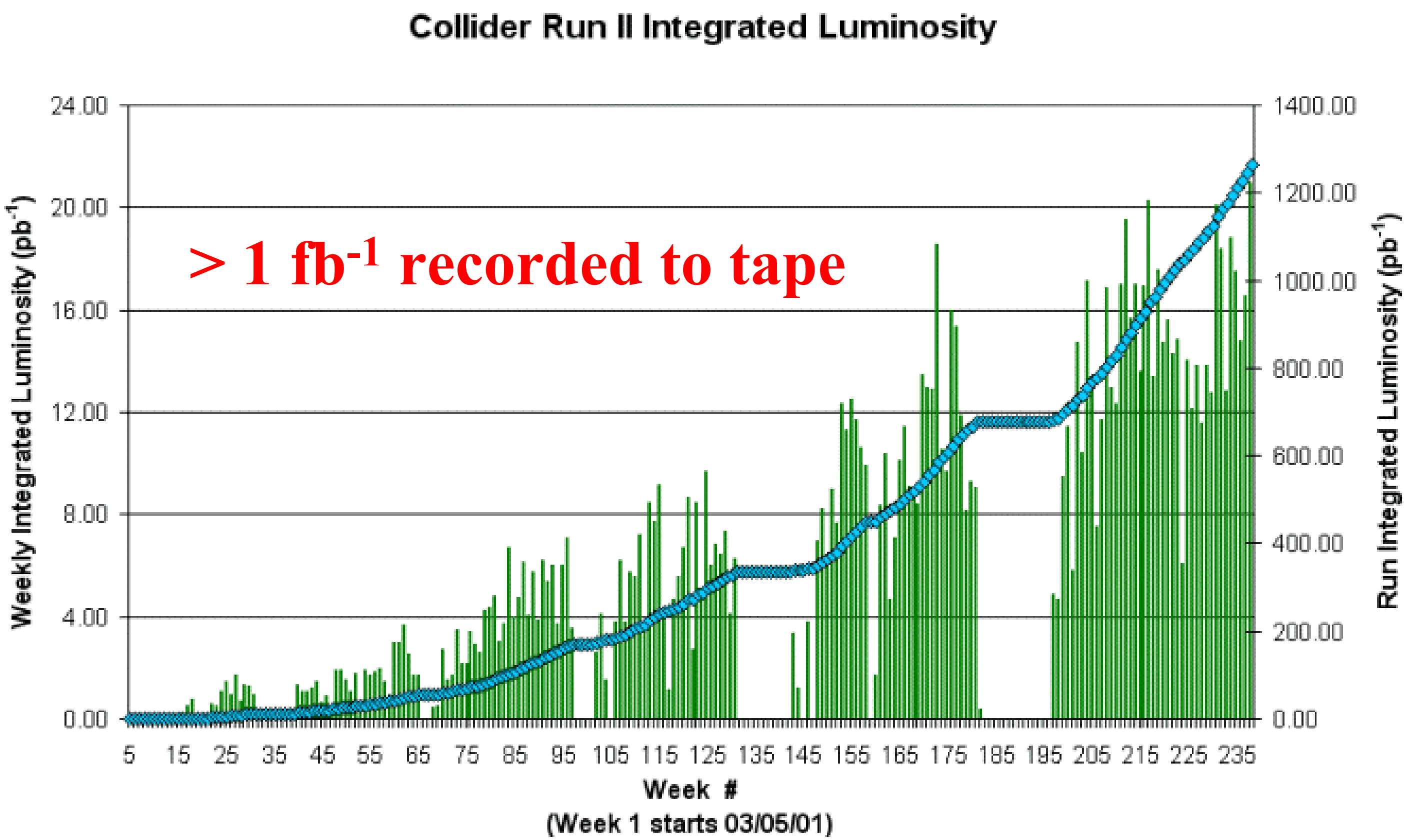


- **Tevatron is highest energy p-pbar collider in the world with CM energy of 1.96 TeV**
- **Weather is quite lovely this time of year!**

Tevatron Performance

Green – weekly integrated luminosity

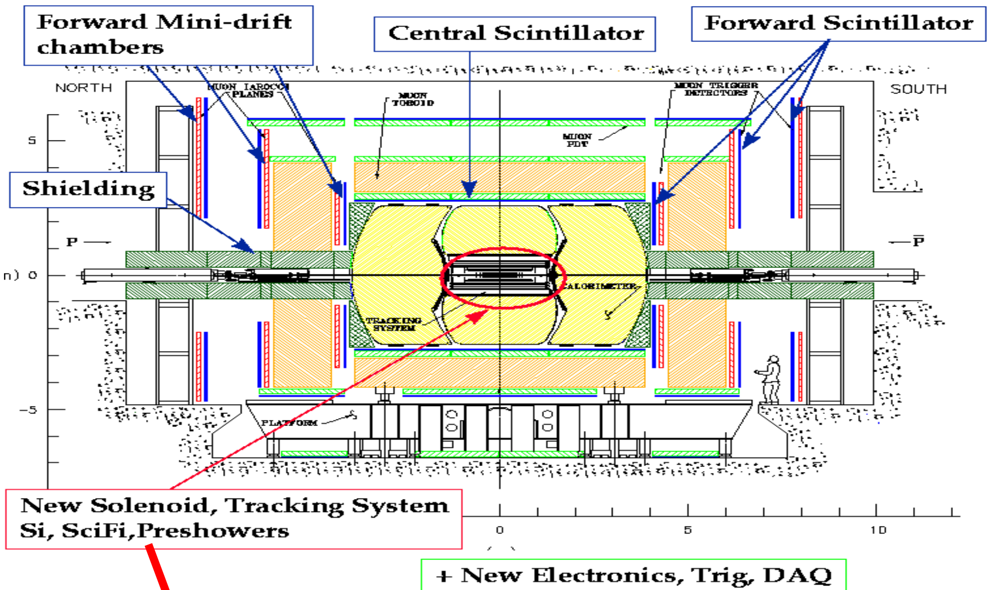
Sky blue – run integrated luminosity



The DØ Collaboration

- 19 Countries
- 86 institutions
- ~676 physicists

The D∅ Detector



Clean Muon ID at |η|<2

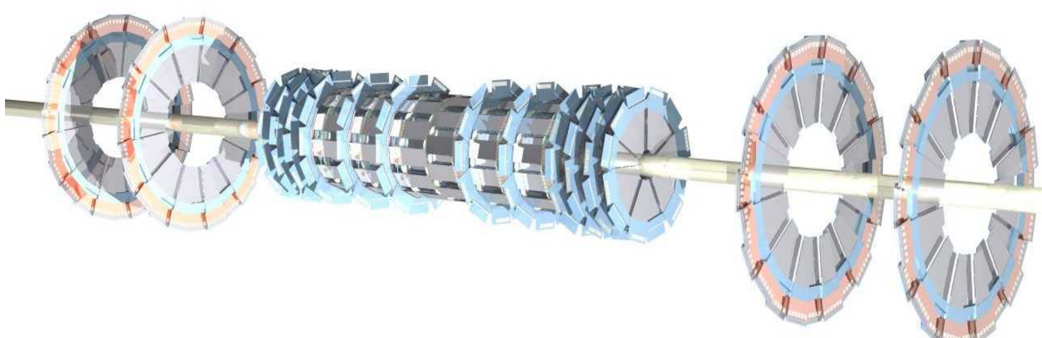
Compact Central Tracker

(r<55 cm)

Good vertex resolution,

Modest p resolution

$\sigma[M(\mu\mu)]$ = 70 MeV at J/ψ



Silicon Microstrip Tracker

- axial hit resolution: ~ 10 μm
- z hit resolution:
  - ~ 35 μm for 90^0 stereo
  - ~ 450 μm for 2^0 stereo

Measurement of the B_s^0 Lifetime

We have measured the lifetime in a semileptonic decay channel

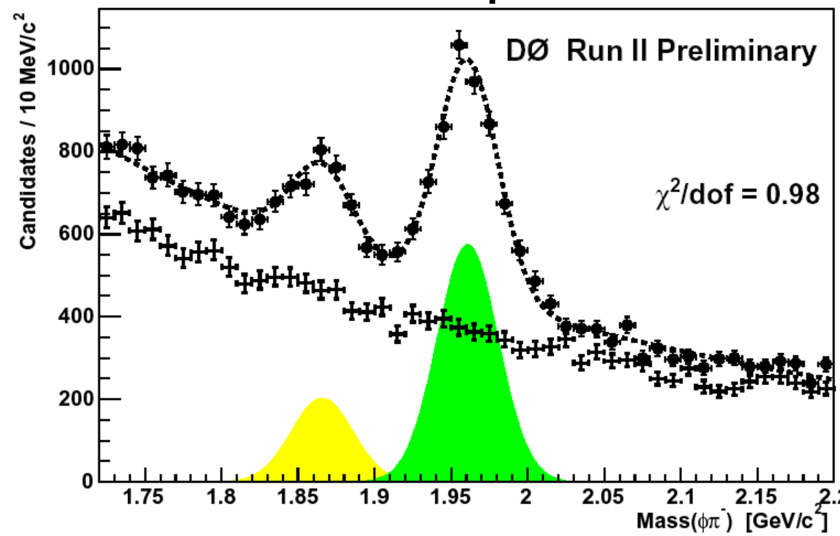
Measure B_s Lifetime Using Decays $B_s \to D_s \mu X$, $D_s \to \phi \pi$, $\phi \to KK$

- Flavor-specific lifetime result used for constraining $\Delta\Gamma/\Gamma$
- Shows we understand the systematics in $B_s \to D_s \mu X$ decays for the Δm_s measurement

Semileptonic B_s

- $B_s \to D_s \mu \nu X$, $D_s \to \phi\ \pi$, $\phi \to KK$
- Large data sample from muon triggers ~400 pb^{-1}
- Include $B \to D_s D$, $D \to \mu$ bkg (MC)
- Include charm background from gluon splitting (wide tails in ct)
- Signal channels

400 pb^{-1}



Sample Composition

25.4% $B_s^0 \to D_s^- \mu^+ \nu X$

67.7% $B_s^0 \to D_s^{*-} \mu^+ \nu X$

2.4% $B_s^0 \to D_{s0}^{*-} \mu^+ \nu X$

4.5% $B_s^0 \to D_{s1}^{'-} \mu^+ \nu X$

Total Br: 7.9 %

Event Selection for Lifetime Analysis $B_s \to D_s \mu X$, $D_s \to \phi \pi$, $\phi \to KK$

Standard selection

- Muon penetrating the toroid
- All tracks within same jet
- χ^2 prob (D_s) > 0.1%
- χ^2 prob (B_s) > 0.01%
- Helicity (D) > 0.4
- L_{xy} (D) · P_T (D) >0

- P_T (μ) > 2.0 GeV
- P_T (K) > 1.0 GeV
- P_T (π) > 0.7 GeV
- P_T (D) > 3.5 GeV
- P_T (μ w.r.t D) > 2 GeV

- 1.008 < M (ϕ) < 1.032 GeV
- 1.6 < M (D_s) < 2.3 GeV
- 3.0 < M (B_s) < 5.0 GeV

We make no L_{xy} cut because we are measuring the lifetime!

B_s Semileptonic Lifetime Fit

Unbinned maximum likelihood fitting components:

$$L = \prod_{i}^{N_s} [f_{sig} F^i_{sig} + (1 - f_{sig}) F^i_{bg}] \prod_{j}^{N_B} F^j_{bg}$$

$$c\tau = L_{xy} \frac{m(B_s)}{P_T(D_s \mu)} \times K$$

$$F^i_{sig} = \int dK H(K) [\frac{K}{c\tau} e^{-K\lambda_j / c\tau} \otimes G]$$

$$F^j_{bg} = (1 - f_+ - f_{++} - f_-) G$$

$$+ f_+ \frac{e^{-\lambda_j / \lambda^+}}{\lambda^+} \quad (\lambda_j \geq 0)$$

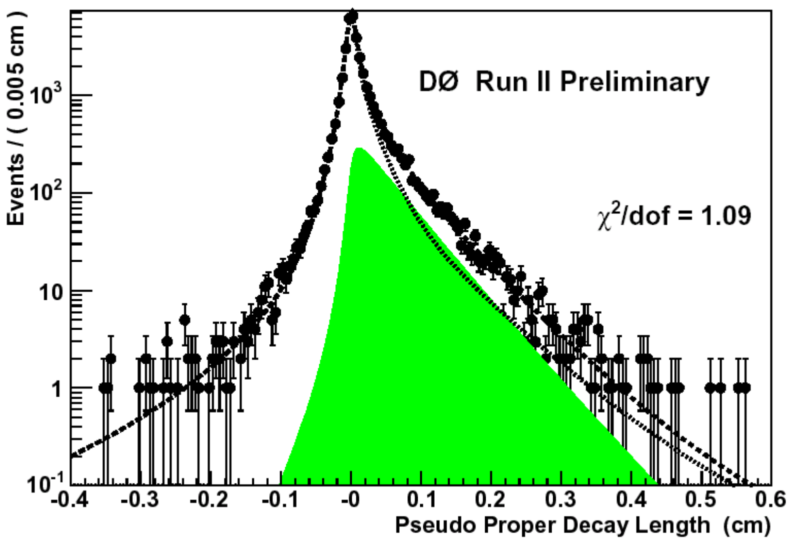
$$+ f_{++} \frac{e^{-\lambda_j / \lambda^{++}}}{\lambda^{++}} \quad (\lambda_j \geq 0)$$

$$+ f_- \frac{e^{-\lambda_j / \lambda^-}}{\lambda^-} \quad (\lambda_j < 0)$$

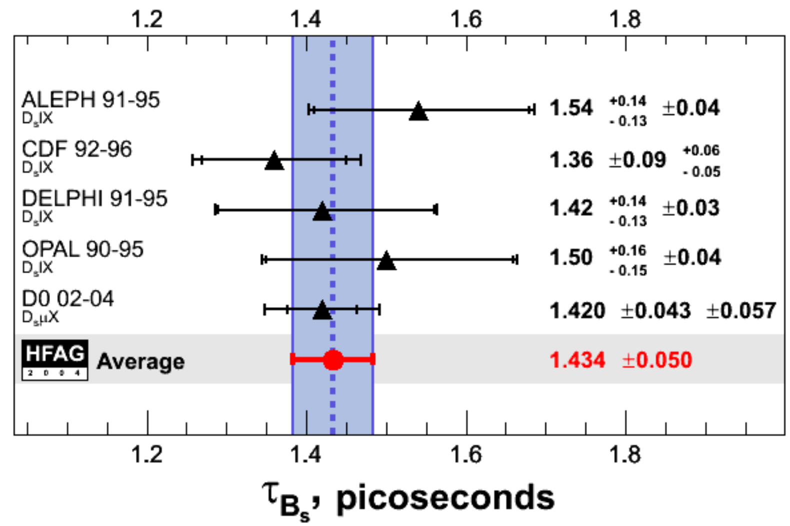
- Signal lifetime
- Background lifetimes
- Signal fraction from D_s mass peak
- Momentum resolution, for each decay mode and type j, K_j
- ct resolution scale factor
- 10 parameters

B_s Semileptonic Lifetime: Results

400 pb^{-1}



Green: signal
Dotted line: background



World's best single measurement !

τ = 1.420 ± 0.043 (stat) ± 0.057 (syst) ps

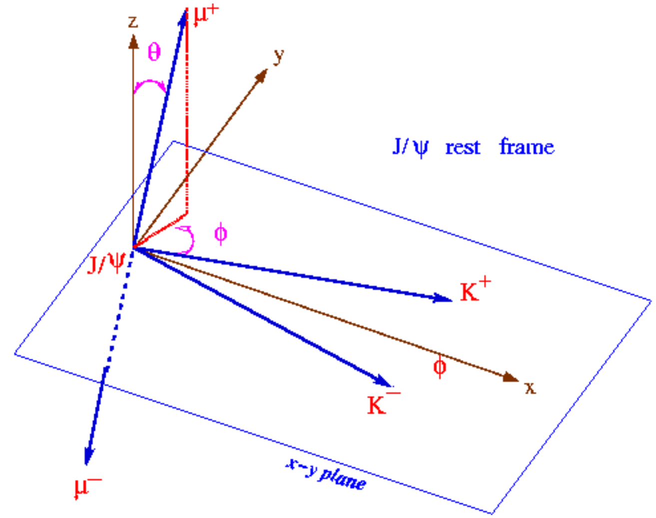
PDG World Average: 1.442 ± 0.066 ps

Lifetime Difference in the B_s^0 System

Untagged B_s Decay

$\cos\theta$=transversity

$B_s \to J/\psi\ \phi$,
Pseudoscalar → Vector Vector decay

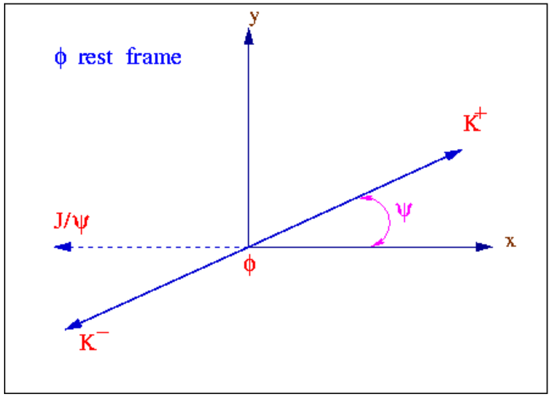


Three waves: S, P, D, or A_0, $A_{||}$, $A_\perp$

Both CP-even and CP-odd present, but well separated in transversity

S, D (Parity, CP even) :
linear combination of A_0, $A_{||}$

P (Parity, CP odd) : $A_\perp$

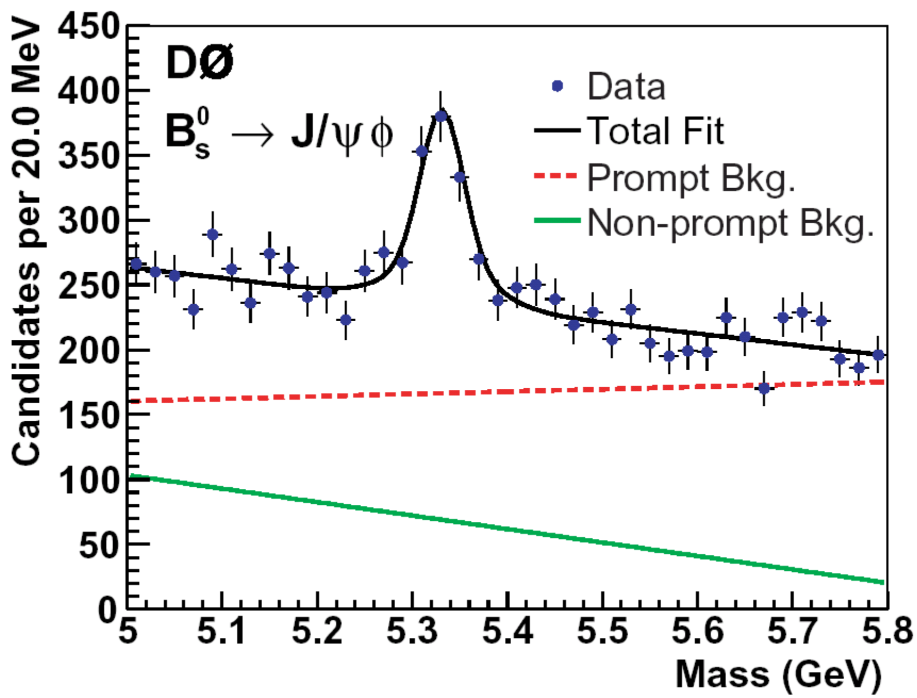


$$\frac{d\Gamma(t)}{d\cos\theta} \propto \left(\left|A_0(t)\right|^2 + \left|A_{||}(t)\right|^2\right)\frac{3}{8}\left(1+\cos^2\theta\right) + \left|A_\perp(t)^2\right|\frac{3}{4}\sin^2\theta$$

Integral for flat efficiency in ϕ, ψ

B_s Lifetime Difference

- We measure **TWO** distinct lifetimes by fitting the **time evolution** and **transversity** distribution in **untagged $B_s \rightarrow J/\psi\ \phi$** decays
- If CP is conserved, they can be interpreted as the lifetimes of the two **B_s mass eigenstates.**



hep-ex/0507084

Maximum Likelihood Fit

$$\mathcal{L} = \prod_{i=1}^{N}[f_{sig}\mathcal{F}^{i}_{sig} + (1 - f_{sig})\mathcal{F}^{i}_{bck}]$$

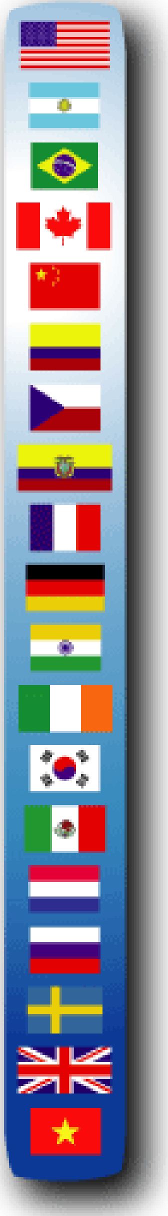
Simultaneous fit to mass, proper decay length and transversity using an unbinned maximum log-likelihood method

19 parameters:

1	f_{sig}	signal fraction
2	signal mass, width	
1	$R_{\perp}$	CP-odd fraction at t = 0
1	$c\tau = c / \bar{\Gamma}$,	$\bar{\Gamma} = (\Gamma_L + \Gamma_H) / 2$
1	$\Delta\Gamma / \bar{\Gamma}$	
2	bkg slope in mass (1 prompt, 1 long-lived)	
1	σ (ct) scale	
6	bkg ct shape	
4	bkg transversity (2 prompt + 2 long-lived)	

Untagged B_s Decay Rate in Time, Angles

$$
\begin{aligned}
\frac{d^3\Gamma\,(\to J/\psi(\to l^+l^-)\,\phi(\to K^+K^-))}{d\cos\theta\; d\phi\; d\cos\psi\; dt} \propto \frac{9}{16\pi}\Big[\, & 2|A_0(0)|^2\, e^{-\Gamma_L t}\cos^2\psi\,(1-\sin^2\theta\,\cos^2\phi) \\
& + \sin^2\psi\,\left\{|A_{\parallel}(0)|^2\, e^{-\Gamma_L t}\,(1-\sin^2\theta\,\sin^2\phi) + |A_{\perp}(0)|^2\, e^{-\Gamma_H t}\sin^2\theta\right\} \\
& + \frac{1}{\sqrt{2}}\sin 2\psi\,\left\{|A_0(0)||A_{\perp}(0)|\cos(\delta_2-\delta_1)\,e^{-\Gamma_L t}\sin^2\theta\,\sin^2 2\phi\right\} \\
& + \left\{\frac{1}{\sqrt{2}}|A_0(0)||A_{\perp}(0)|\cos\delta_2\,\sin 2\psi\,\sin 2\theta\,\cos\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\delta\phi \\
& - \left\{\frac{1}{\sqrt{2}}|A_{\parallel}(0)||A_{\perp}(0)|\cos\delta_1\,\sin^2\psi\,\sin 2\theta\,\sin\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\delta\phi\,\Big]\; H(\cos\psi)\,F(\phi)\,G(\cos\theta)
\end{aligned}
$$

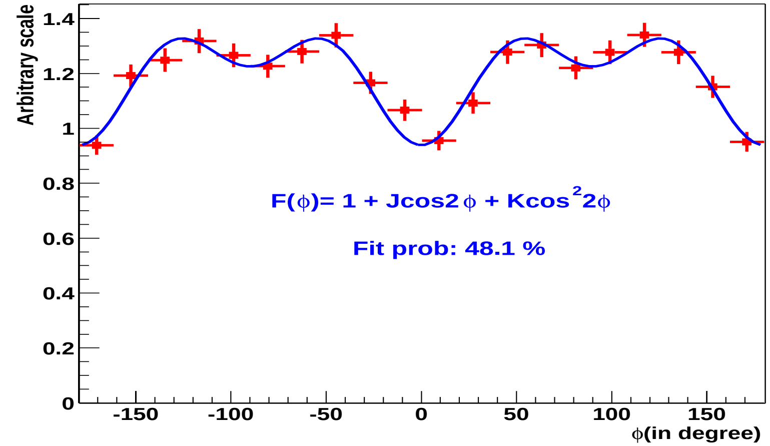


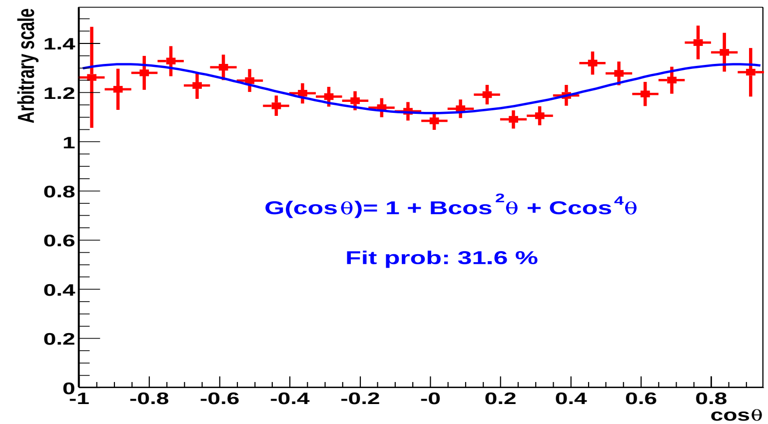
Detector Acceptance (MC)

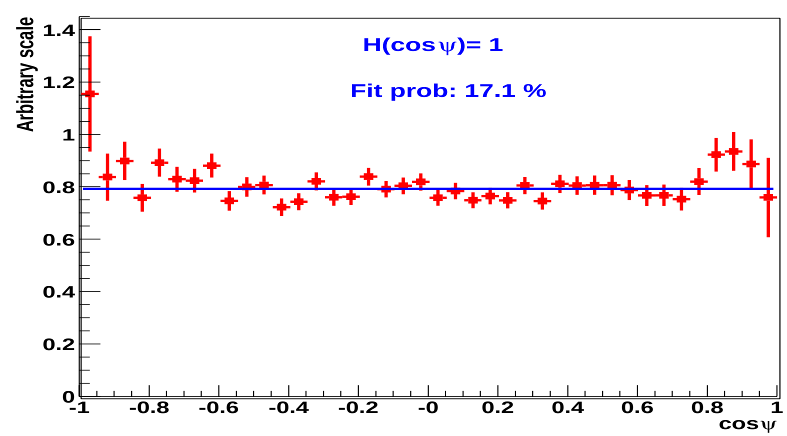
$F(\phi) = 1 + J\cos(2\phi) + K\cos^2(2\phi)$

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

$H(\cos\psi)$ flat distribution







3 Angles → 1 Angle

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

$$
\begin{aligned}
\frac{d^3\Gamma \to J/\psi\,(\to l^+l^-)\,\phi(\to K^+K^-)}{d\cos\theta\, dt} = N\pi \Big[& (|A_0(0)|^2 + |A_{\parallel}(0)|^2)e^{-\Gamma_L t}(1 + \cos^2\theta) \\
& + \frac{K}{2}\Big\{ (|A_0(0)|^2 + |A_{\parallel}(0)|^2)\, e^{-\Gamma_L t}(1 + \cos^2\theta) \quad + 2\,|A_{\perp}(0)|^2\, e^{-\Gamma_H t}\sin^2\theta \Big\} \\
& - \frac{J}{2}(|A_0(0)|^2 - |A_{\parallel}(0)|^2)\, e^{-\Gamma_L t}\sin^2\theta \quad + 2\,|A_{\perp}(0)|^2\, e^{-\Gamma_H t}\sin^2\theta \Big]\; G(\cos\theta)
\end{aligned}
$$

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

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

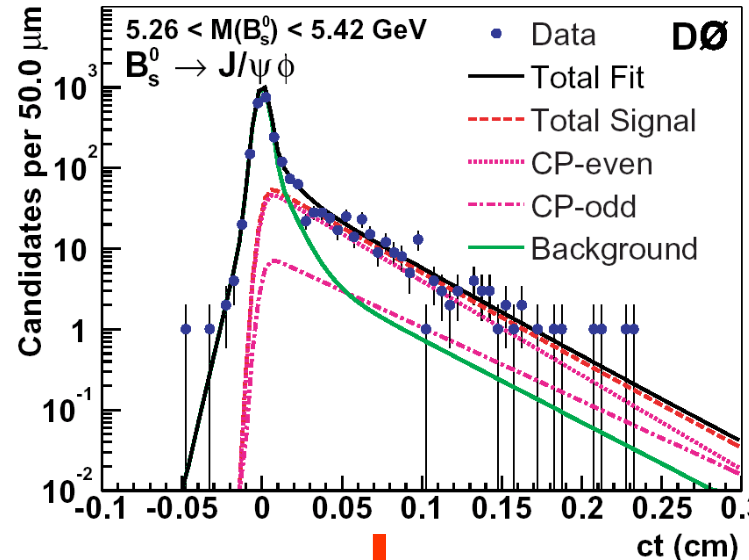
D∅ ΔΓ Result

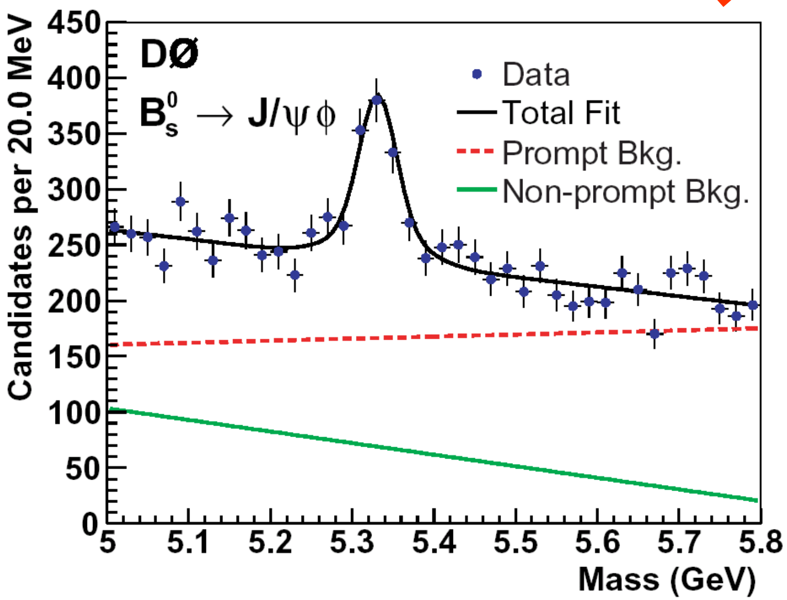
$$\bar{\tau}(B_s^0) = 1.39^{+0.13}_{-0.14} \pm 0.08\, ps$$

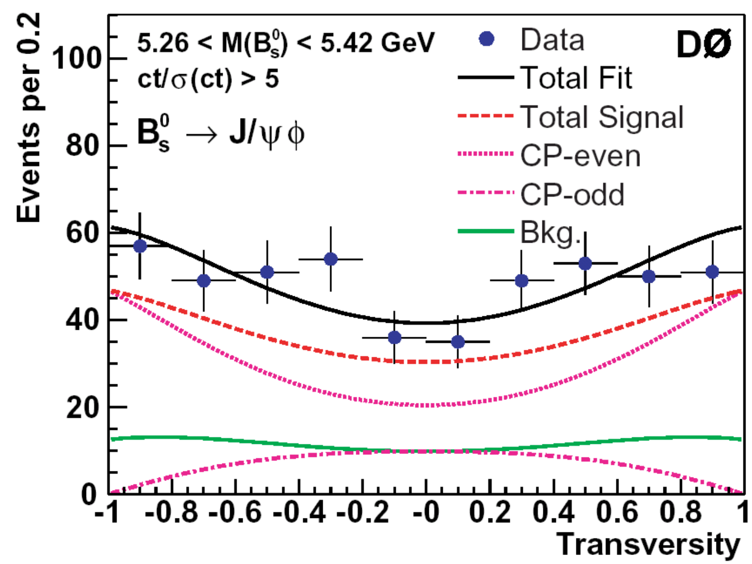
$$\frac{\Delta\Gamma}{\bar{\Gamma}} = 0.21^{+0.27}_{-0.40} \pm 0.20$$

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

Accepted by PRL !

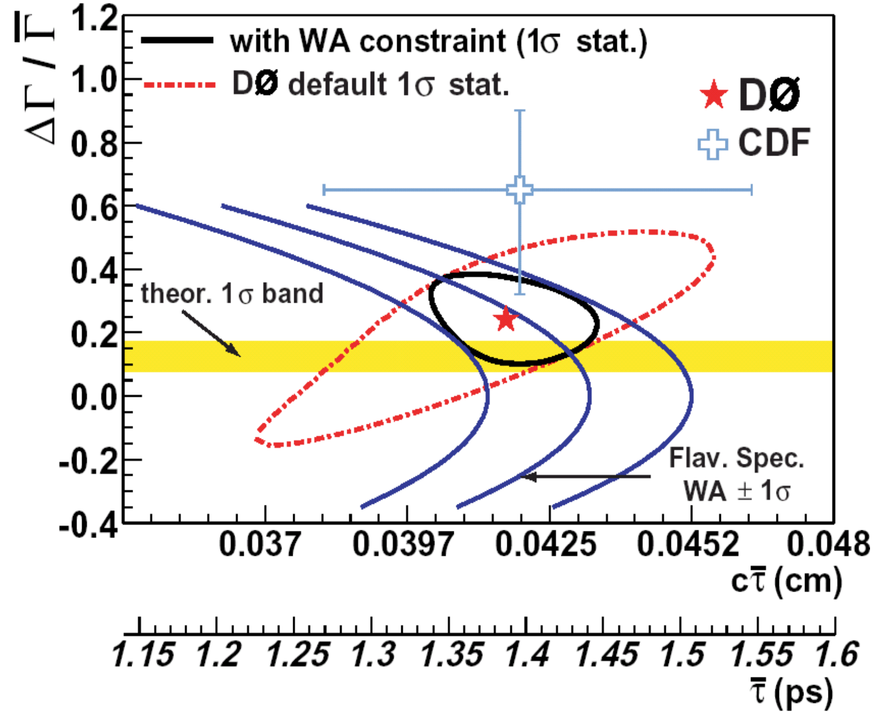






$\Delta\Gamma$ Comparisons

- **D0 and CDF $\Delta\Gamma/\Gamma$ results are consistent**
- **D0 result is close to the theory prediction of 0.12 ± 0.05**

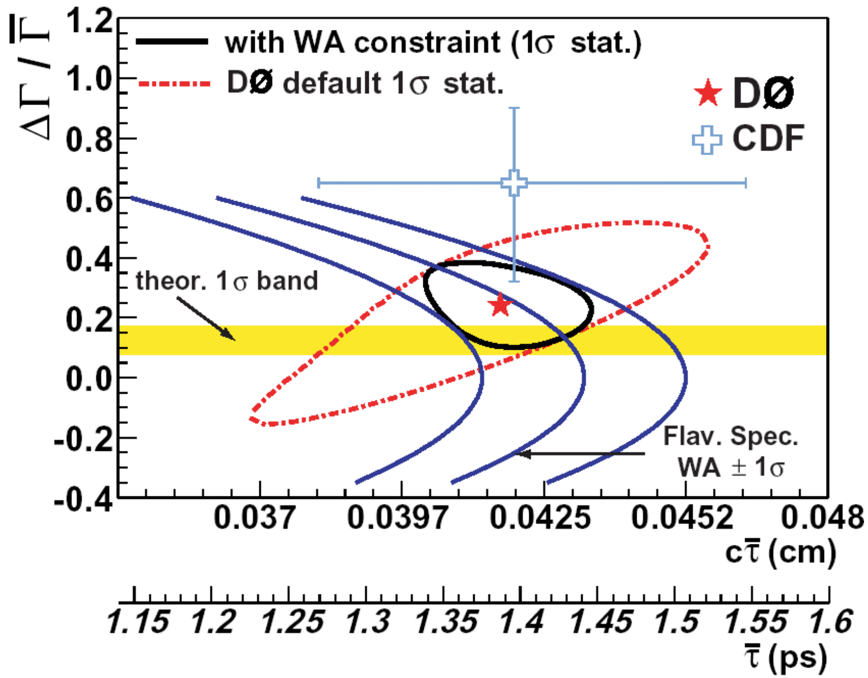


Including systematic errors:

$Experiment$	$R_\perp$	$\Delta\Gamma/\Gamma$	$\bar{\tau}(ps)$	τ_L	τ_H
$Aleph$				1.27 ± 0.34	
$CDF\ RunII$	0.125 ± 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 ± 0.10	$0.21^{+0.33}_{-0.45}$	$1.39^{+0.15}_{-0.16}$	$1.23^{+0.16}_{-0.13}$	$1.52^{+0.39}_{-0.43}$

Constraint from Semileptonic Measurements

WA semileptonic (flavor specific) measurements provide an independent relation of $\Delta\Gamma$ and Γ, leading to a significant improvement to $\Delta\Gamma$



A single-lifetime fit applied to flavor specific final state measures $\Gamma_{fs} = 1/\tau_{fs}$:

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

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

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

$\Delta\Gamma/\Gamma$ Projections