$\Delta\Gamma_s/\Gamma_s$ at Tevatron

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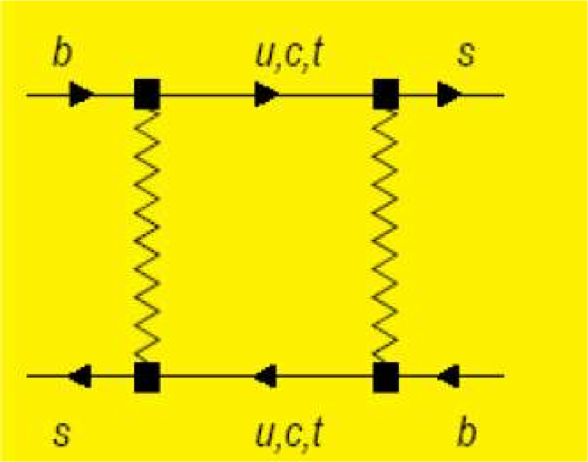
B_s System

Schroedinger Equation:

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



Most general eigenstates :

$$B_L = p|B_s\rangle + q|\bar{B}_s\rangle$$
$$B_H = p|B_s\rangle - q|\bar{B}_s\rangle, \; p^2 + q^2 = 1$$

Heavy and light B_s eigenstates are expected to have different widths

- M_{12} stems from the real part of the box diagram, dominated by top (off-shell)
- Γ_{12} stems from the imaginary part, dominated by charm (on-shell)

$\Delta\Gamma_s$ for Bs

- Relation of matrix elements to decay and oscillation parameters:

$$\Delta m = M_H - M_L \approx 2|M_{12}|$$
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$$

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$\bar{\Gamma}_s = \frac{\Gamma_L + \Gamma_H}{2}$$

In the Standard Model:

- The CP violating phase, ϕ is expected to be small
- Mass eigenstates are ~ CP eigenstates with definite lifetimes
- $\Delta\Gamma_d$ for B_d is expected to be pretty small

- Assuming no CP violation in the B_s system, measure two B_s lifetimes, τ_L and τ_H, (or $\Delta\Gamma_s/\Gamma_s$ and τ) by simultaneously fitting time evolution and angular distribution in not flavor tagged $B_s \rightarrow J/\psi\phi$ decays

Why do we like $B_s \to J/\psi\phi$?

$$B_s \to J/\psi\,\varphi \qquad B_d \to J/\psi\,K^{*0} \quad \begin{cases} J/\psi \to \mu^+\mu^- \\ \varphi \to K^+K^- \\ K^{*0} \to K^-\pi^+ \end{cases}$$

- Angular momenta: $P \to VV$

- Total J of final state = 0
- Two spin-1 $\Rightarrow$ J = 0, 1, 2
- Orbital L = 0, 1, 2 (S, P, D wave)

$\Rightarrow$ Need 3 amplitudes (partial wave, helicity or transversity)

- S, D wave = Parity Even, (CP Even for $J/\psi\phi$)
- P wave = Parity Odd, (CP Odd for $J/\psi\phi$)
- B_s is unknown mixture of CP states

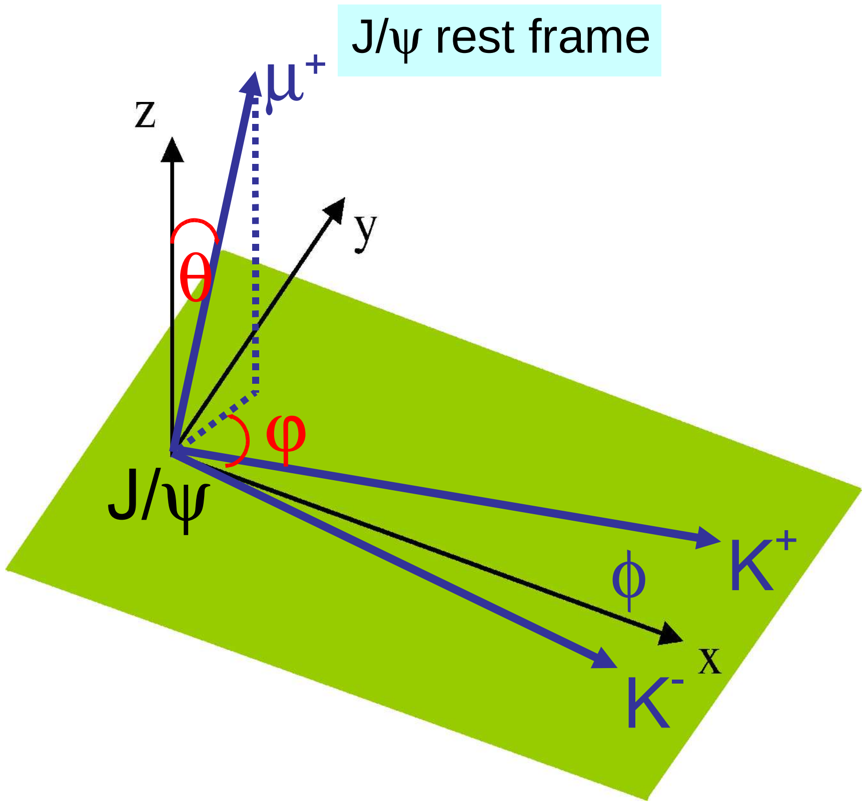
Separates CP states nicely

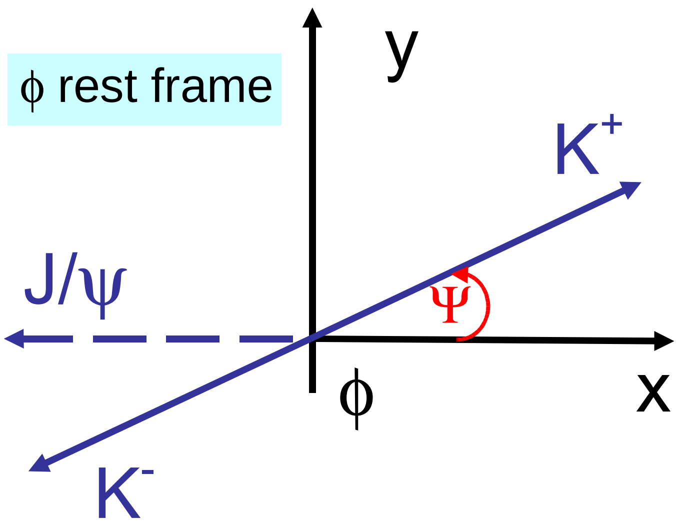
$$B_s^H = \frac{1}{\sqrt{2}}\left(|B_s\rangle + |\overline{B}_s\rangle\right) = CP-odd$$

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

Disentangle different L- components of decay amplitudes $\Rightarrow$ isolate two B states

Angle definitions





KK plane defines (x,y) plane
K^+(K) defines +y direction
θ,φ polar and azimuthal angles of μ^+
Ψ helicity angle of ϕ(K*)

Angular Decay Distributions

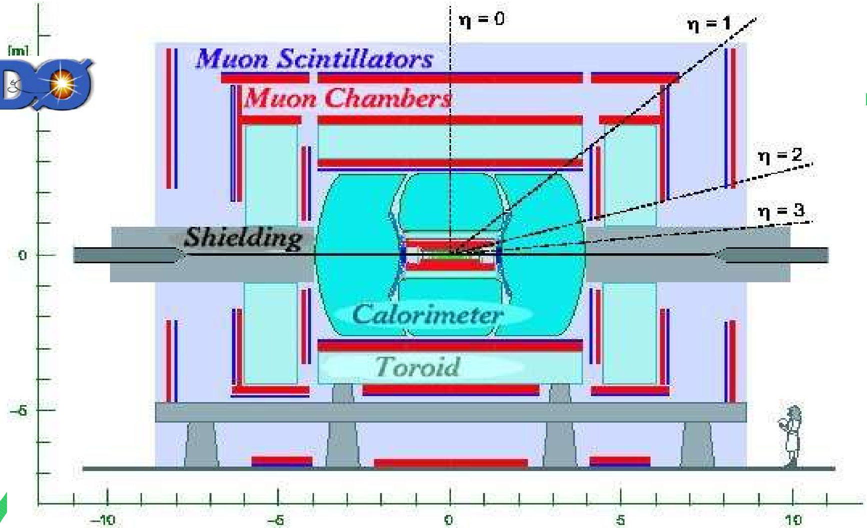
$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot g_1(t) \cdot f_1(\vec{\rho}) + |A_{||}|^2 \cdot g_2(t) \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot g_3(t) \cdot f_3(\vec{\rho}) \pm Im(A_{||}^* A_\perp) \cdot g_4(t) \cdot f_4(\vec{\rho}) + Re(A_0^* A_{||}) \cdot g_5(t) \cdot f_5(\vec{\rho}) \pm Im(A_0^* A_\perp) \cdot g_6(t) \cdot f_6(\vec{\rho}) \equiv \sum_{i=1}^{6} \mathcal{A}_i \cdot g_i(t) \cdot f_i(\vec{\rho})$$

$$\begin{aligned}
f_1(\vec{\rho}) &= 2\cos^2\psi(1 - \sin^2\theta\cos^2\phi) \\
f_2(\vec{\rho}) &= \sin^2\psi(1 - \sin^2\theta\sin^2\phi) \\
f_3(\vec{\rho}) &= \sin^2\psi\sin^2\theta \\
f_4(\vec{\rho}) &= -\sin^2\psi\sin 2\theta\sin\phi \\
f_5(\vec{\rho}) &= \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi \\
f_6(\vec{\rho}) &= \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi
\end{aligned}$$

A. Dighe et al., Eur. Phys. J. C6, 647

A_0 = longitudinal polarization amplitude
$A_{||}$, $A_\perp$ = transversity polarization amplitudes

Tevatron detectors

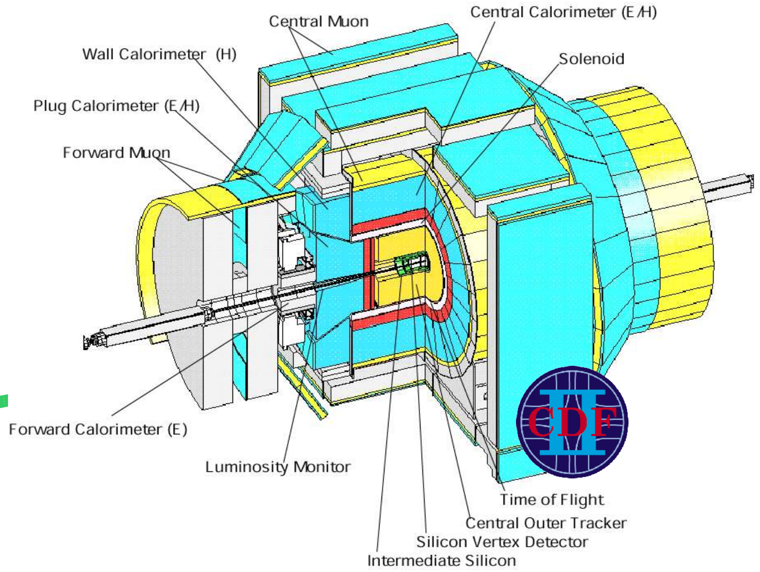


CDF

- Excellent Tracking
  - Silicon Layer00: r_{L00} = 1.3cm
  - Drift Chamber: 96 layers
- Hadronic Triggers
- Particle ID by dE/dx and TOF

DØ

- Excellent Coverage
  - Muon System: $|\eta| < 2$
  - Tracking System: $|\eta| < 3$
- Robust Muon Triggers
- High Yields



CDF: Fit Distributions

B_s:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot e^{-\Gamma_L t} \cdot f_1(\vec{\rho}) + |A_\parallel|^2 \cdot e^{-\Gamma_L t} \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot e^{-\Gamma_H t} \cdot f_3(\vec{\rho}) + Re(A_0^* A_\parallel) \cdot e^{-\Gamma_L t} \cdot f_5(\vec{\rho})$$

- flavor blind decay
- $\delta\phi_{CPV} \approx 0.03$

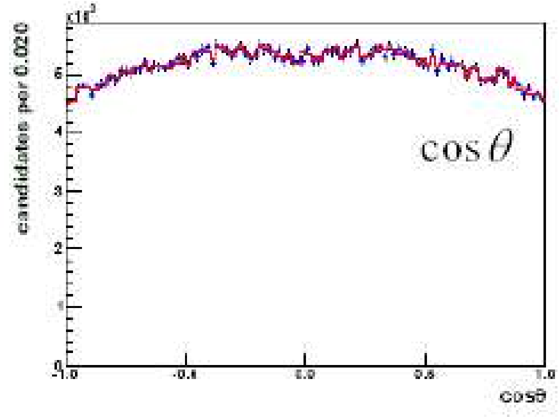
B_d:

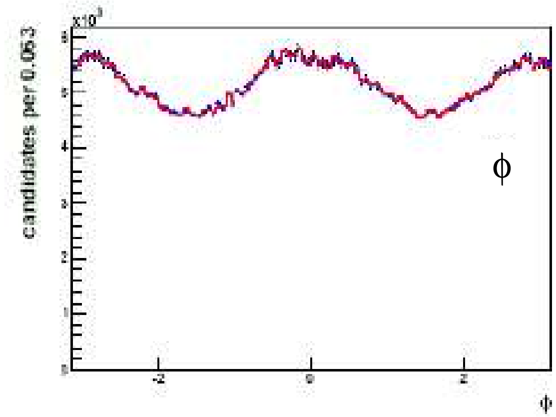
$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto \Big\{ |A_0|^2 \cdot f_1(\vec{\rho}) + |A_\parallel|^2 \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot f_3(\vec{\rho}) \pm Im(A_\parallel^* A_\perp) \cdot f_4(\vec{\rho}) + Re(A_0^* A_\parallel) \cdot f_5(\vec{\rho}) \pm Im(A_0^* A_\perp) \cdot f_6(\vec{\rho}) \Big\} \cdot e^{-\Gamma_d t}$$

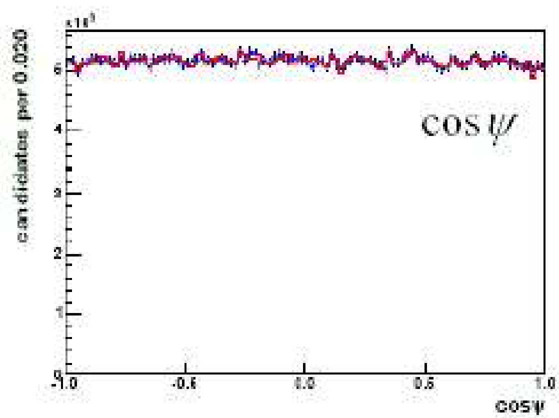
- flavor specific decay
- $\delta\phi_{CPV} = 2\beta$

Detector efficiency is taken into account as global terms (no correlations)

CDF: Detector Acceptance







- 40M decays generated with flat angular distributions
- These shapes shown the effect of the cuts and detector sculpting

DØ: Transversity Analysis

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

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

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

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

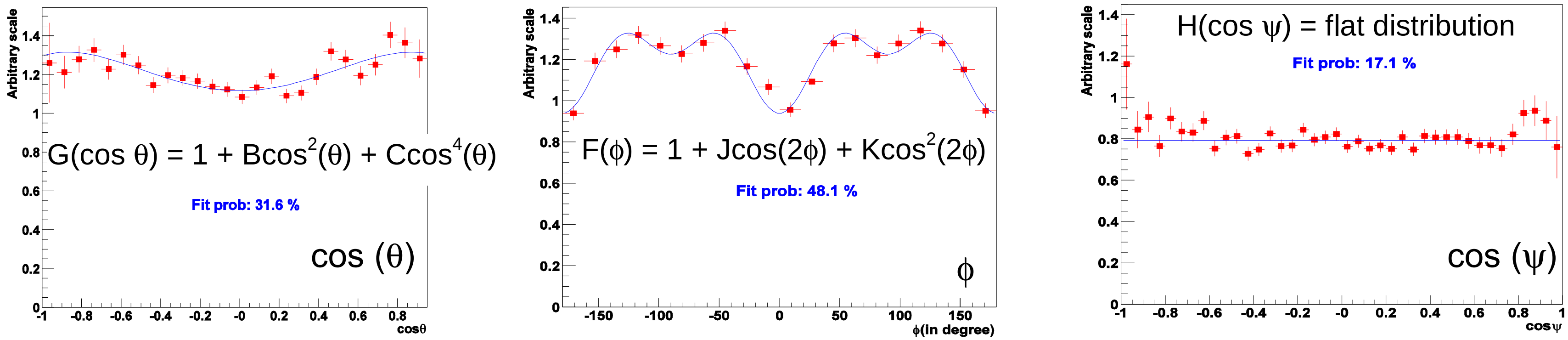
$$- \left\{\frac{1}{\sqrt{2}}|A_{||}(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\delta\phi\,\Big]\; H(\cos\psi)\,F(\phi)\,G(\cos\theta)$$

Full angular distribution

Sensitivity to CP violation if $\Delta\Gamma_s/\Gamma_s$ is sizable

Detector acceptance

DØ: Three Angles to One Angle



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

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

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

CP even term

CP odd term

Interference of amplitudes
0.355 ± 0.066 (from CDF)
analysis does not depend on this

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

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

Likelihood Fit

Simultaneous fit to mass, proper decay length and angular distributions using an un-binned maximum log-likelihood method

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

CDF:

f_{sig}	signal fraction
$\tau = 1/\Gamma$,	$\Gamma = (\Gamma_L + \Gamma_H)/2$
$A_0, A_{\|\|}, A_\perp$	angular info at t=0
$\Delta\Gamma / \overline{\Gamma}$	
M_B	mass of B

DØ:

f_{sig}	signal fraction
$\tau = 1/\Gamma$,	$\Gamma = (\Gamma_L + \Gamma_H)/2$
$R_\perp$	CP-odd fraction at t=0
$\Delta\Gamma / \overline{\Gamma}$	
M_B	mass of B

Plus resolution, background parameters (mass,PDL,angular): ~14

CDF: Fit results

CDF uses 260 pb^{-1}

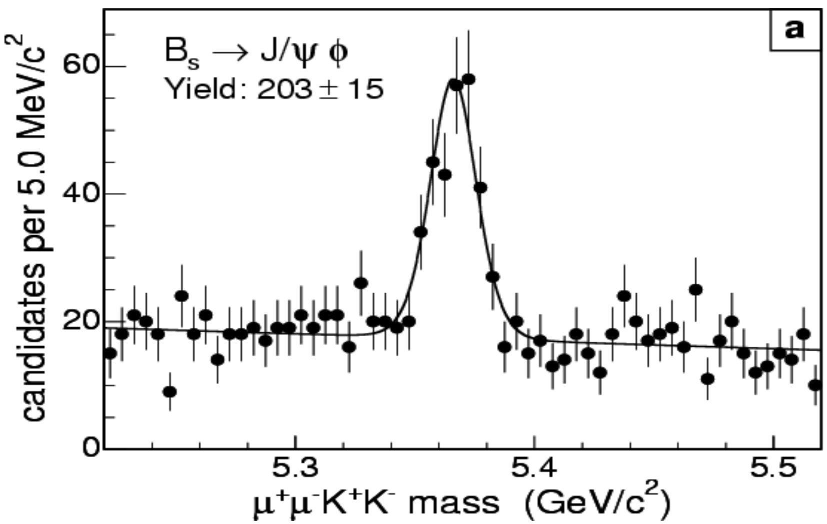
$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02$ ps

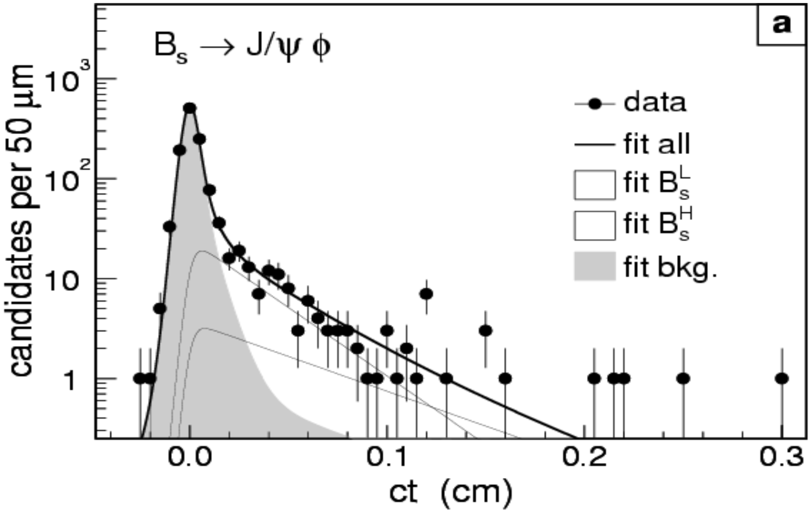
$\tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03$ ps

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

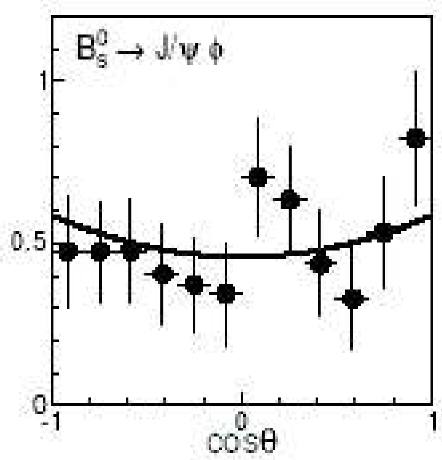
$\Delta\Gamma_s/\Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$

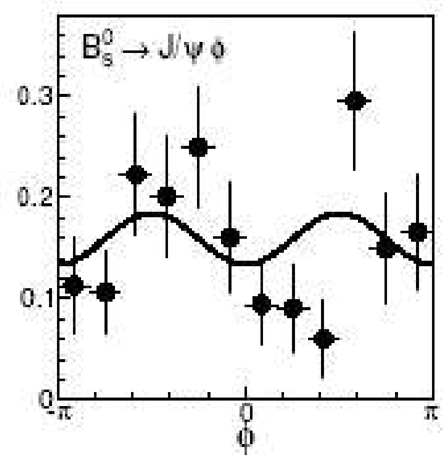
PRL 94, 10180, (2005)





CDF: Fit results





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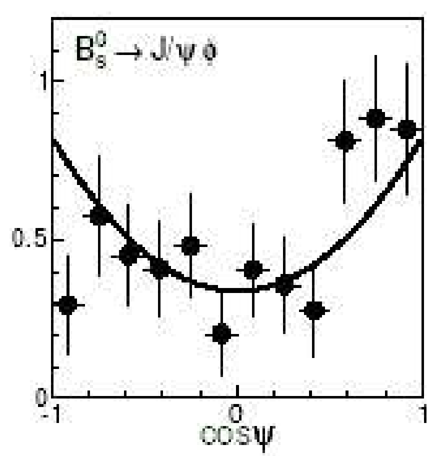


In addition the fit provide angular information of the system

Distributions are normalized, background subtracted and acceptance corrected.

DØ: Fit Results

DØ uses 450 pb^{-1}

DØ preliminary

$$\bar{\tau}(B_s^0)=\frac{1}{\bar{\Gamma}_s}=1.39^{+0.13}_{-0.14}\pm0.08\ \text{ps}$$

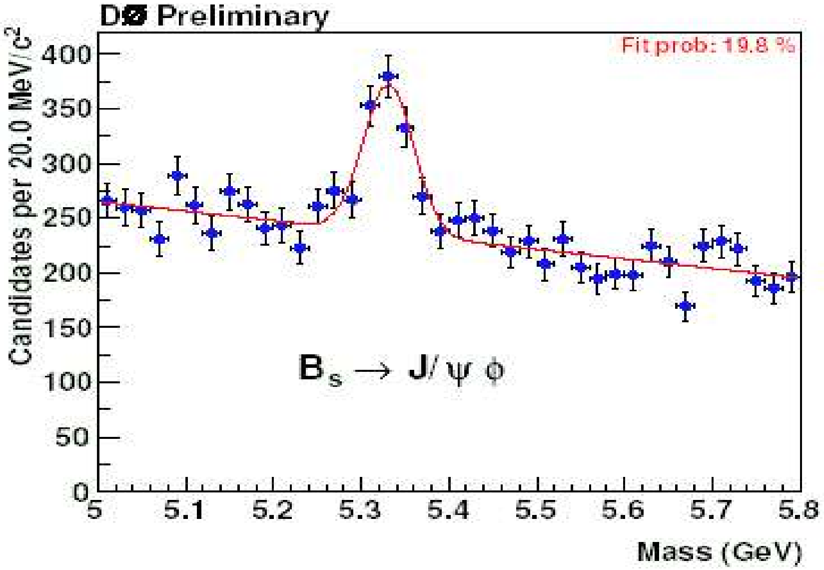
$$\frac{\Delta\Gamma_s}{\bar{\Gamma}_s}=0.21^{+0.27}_{-0.40}\pm0.20$$

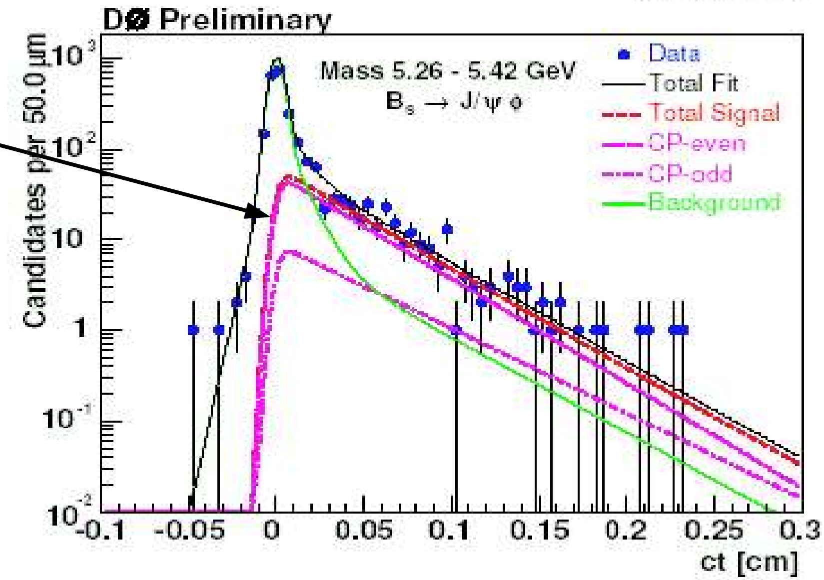
$$R_{\perp}=0.17\pm0.10\pm0.02$$

$$\tau_L=1.23^{+0.14}_{-0.11}\,(\text{stat})\ \text{ps}$$

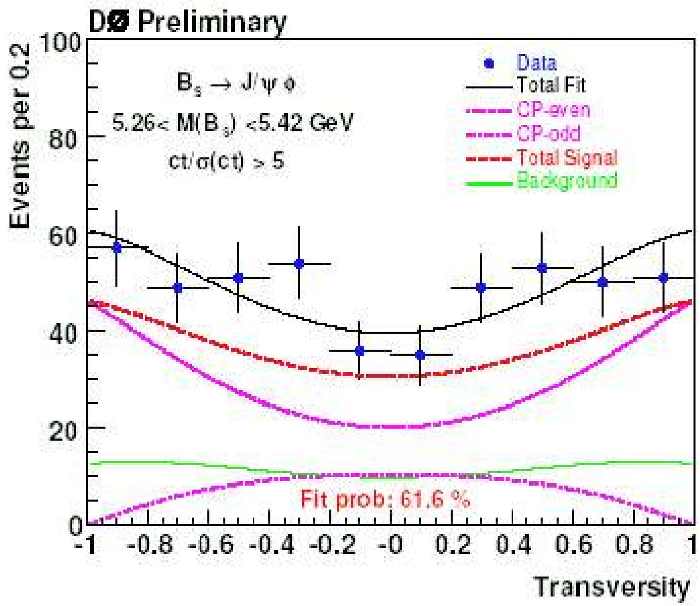
$$\tau_H=1.52^{+0.39}_{-0.43}\,(\text{stat})\ \text{ps}$$

$$\bar{\Gamma}_s=\frac{\Gamma_L+\Gamma_H}{2}$$



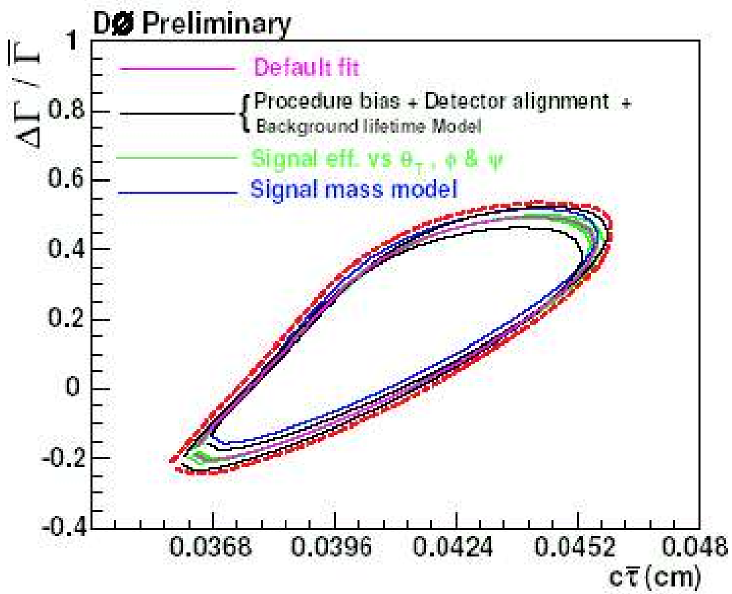


DØ: Fit results



Information for the angle studies:
Transversity = cos (θ)

1σ contour for fitted parameters



CDF: Systematic Errors

Source	$c\tau_s(\mu m)$	$\Delta\Gamma_s/\Gamma_s$	A_0	$A_\parallel$	$A_\perp$	$\delta_\parallel$
Bkg Model	3.70	0.007	0.007	0.013	0.003	0.03
B_d Cross feed	5.00	0.008	-	0.030	0.001	-
Lifetime	2.40	-	-	-	-	-
Total	6.70	0.011	0.007	0.013	0.003	0.03

PRL 94, 10180, (2005)

DØ: Systematic Errors

Source	$c\tau_s(\mu m)$	$\Delta\Gamma_s/\Gamma_s$	$R_\perp$	Comment
Signal ε vs $\cos(\theta)$	0.6	0.001	0.005	MC
Signal ε vs ϕ, ψ angles including: $(\lvert A_0\rvert^2 - \lvert A_{\parallel}\rvert^2)$	0.2	0.001	0.020	MC + CDF
Signal mass model	0.4	0.016	0.006	DATA
Procedure bias	2	0.025	0.010	MC
Detector alignment	2	-	-	DATA
Bkg lifetime model	0.5	0.016	0.005	DATA

DØ preliminary

CDF: Additional constraint

Constraining $\tau_s = 2\,\tau_L\,\tau_H / (\tau_L + \tau_H) = \tau_d = 460.8 \pm 4.2\,(\text{stat}) \pm 4.6\,(\text{syst})\ \mu\text{m}$

$\tau_L = 1.13^{+0.13}_{-0.09} \pm 0.02$ ps

$\tau_H = 2.38^{+0.56}_{-0.43} \pm 0.03$ ps

$\Gamma_s = 0.46 \pm 0.18 \pm 0.01\ \text{ps}^{-1}$

$\Delta\Gamma_s/\Gamma_s = 0.71^{+0.24}_{-0.28} \pm 0.01$

Only small change in result after constraint

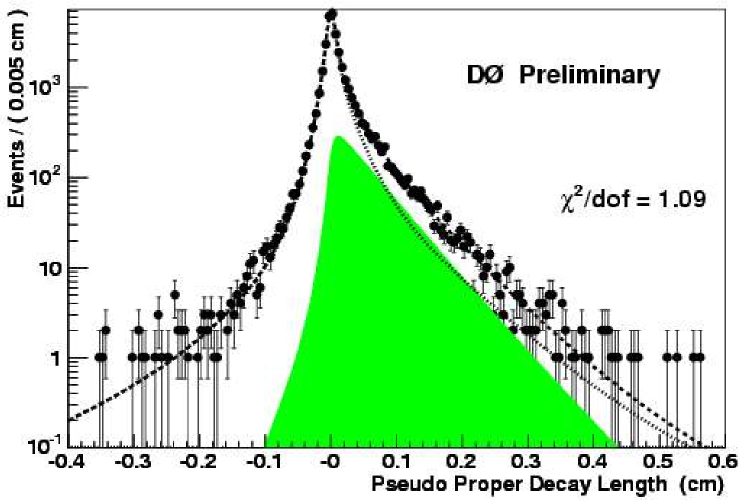
DØ: Additional constraint

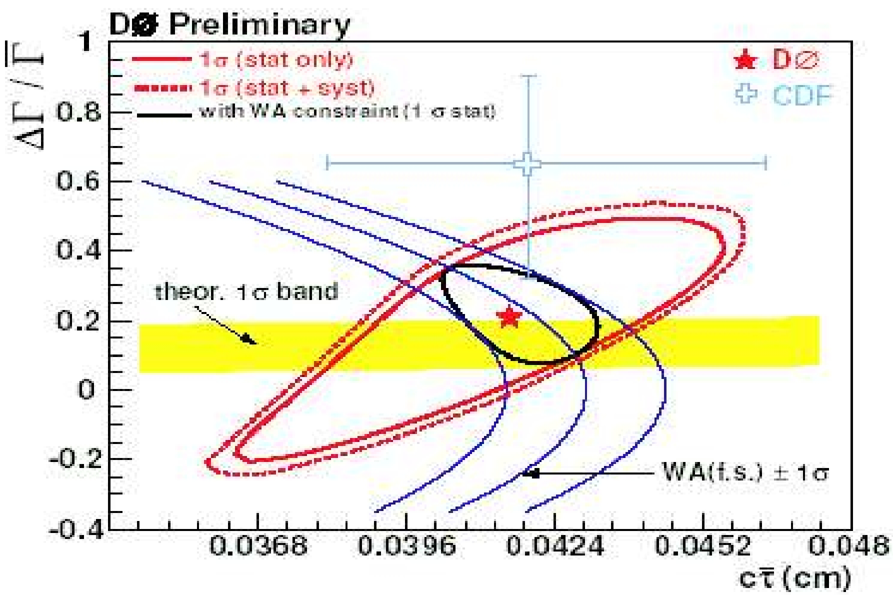
B_s Lifetime from flavor specific decay (e.g. B_s or $\overline{B}_s$)

- $B_s \rightarrow D_s \mu \nu X$
- Large data sample from muon triggers ~ 400 pb^{-1}
- Take *K* distribution from several semi-leptonic modes
- Include charm and bottom backgrounds in the fit

DØ pre.: $\tau(B_s)$ = 1.420 ± 0.043 (stat) ± 0.057 (syst) ps

WA: $\tau(B_s)$ = 1.434 ± 0.050 ps

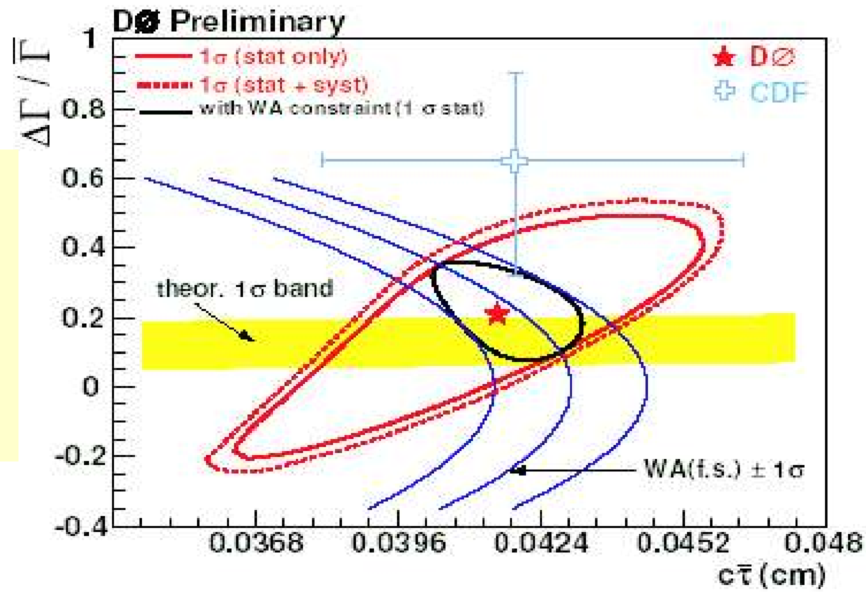




$$c\tau = c\tau(\text{f.s.}) \frac{1 - \left(\frac{\Delta\Gamma}{2\overline{\Gamma}}\right)^2}{1 + \left(\frac{\Delta\Gamma}{2\overline{\Gamma}}\right)^2}$$

Comparisons

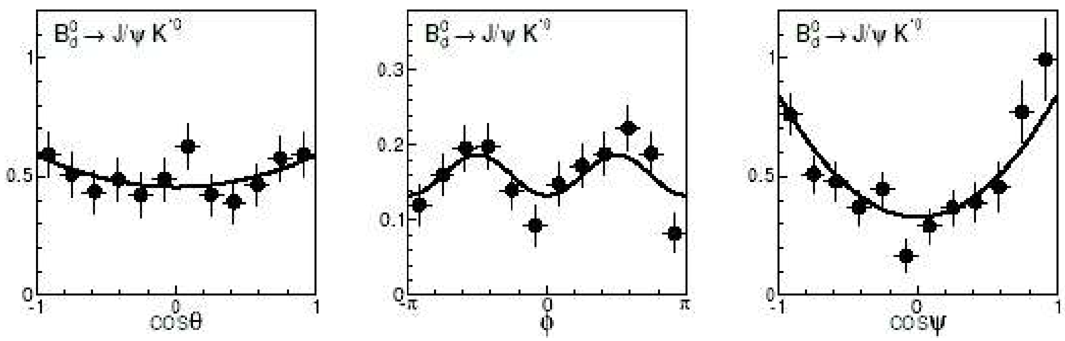
- DØ and CDF $\Delta\Gamma_s/\Gamma_s$ results are consistent
- DØ result is close to the theory prediction of 0.12±0.05
- The WA flavor specific lifetime provides significant improvement to $\Delta\Gamma_s$



Experiment	$R_\perp$	$\Delta\Gamma_s/\Gamma_s$	$\bar{\tau}$ (ps)	τ_L (ps)	τ_H (ps)
Aleph				1.27±0.34	
CDF RunII	0 .125±0.08	$0.65^{+0.25}_{-0.33}$	$1.40^{+0.15}_{-0.13}$	$1.05^{+0.16}_{-0.13}$	$2.07^{+0.58}_{-0.46}$
DO RunII	0.17±0.10	$0.21^{+0.33}_{-0.45}$	$1.39^{+0.15}_{-0.16}$	$1.23^{+0.16}_{-0.13}$	$1.52^{+0.39}_{-0.43}$

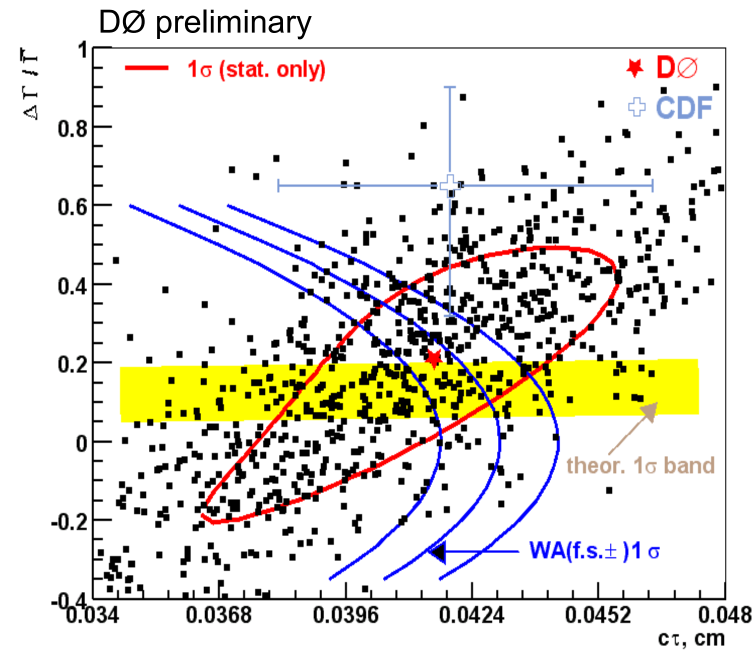
Cross checks

CDF: B_d consistent with BELLE and BaBar



CDF: Fit consistent with expected

ct cut	B_s^0 fitted	B_s^0 expected	B_d^0 fitted
$> 0\,\mu m$	20 ± 9	20 (reference)	22 ± 4
$> 150\,\mu m$	24 ± 10	24	23 ± 4
$> 300\,\mu m$	30 ± 13	29	23 ± 4
$> 450\,\mu m$	39 ± 12	34	24 ± 5



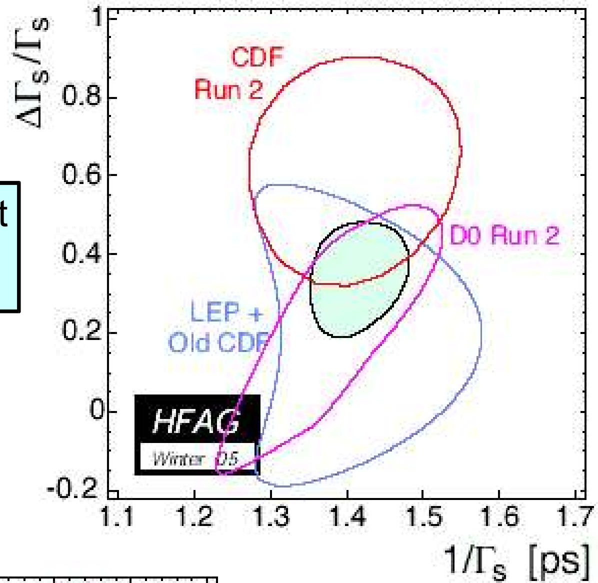
CDF ensemble test:
1/325 could be $\Delta\Gamma_s/\Gamma_s = 0$
1/84 could be $\Delta\Gamma_s/\Gamma_s = 0.12$

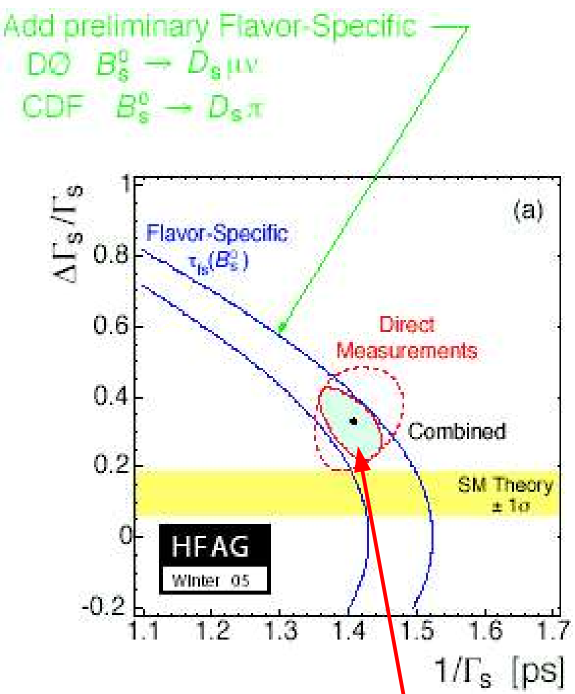
DØ ensemble test:
~70% "experiments" give $\Delta\Gamma_s/\Gamma_s$ and $c\tau$ within 1 RMS
~5% "experiments" give $\Delta\Gamma_s/\Gamma_s > 0.65$ (CDF value)

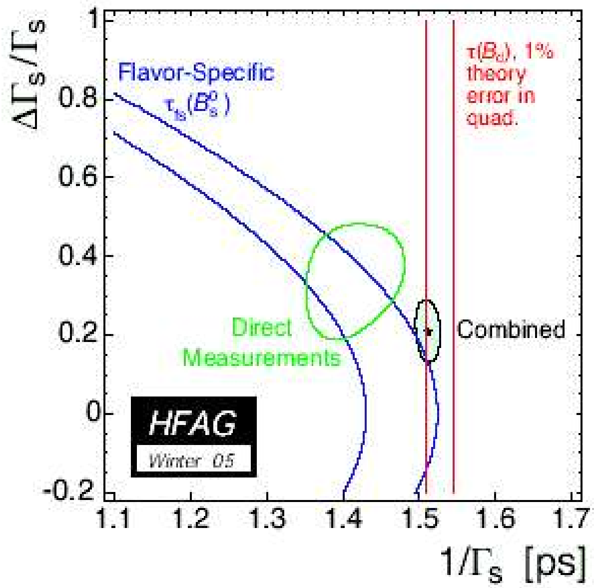
Averages from HFAG

combining all current measurements

hep-ex/0505100







clearly $\tau(B_s)/\tau(B_d)$ is not in the 0.99-1.01 range, but ...
anyway, applying constraint

$$\bar{\tau} = \frac{1}{\Gamma_s} = 1.405^{+0.043}_{-0.047}\ \text{ps}$$

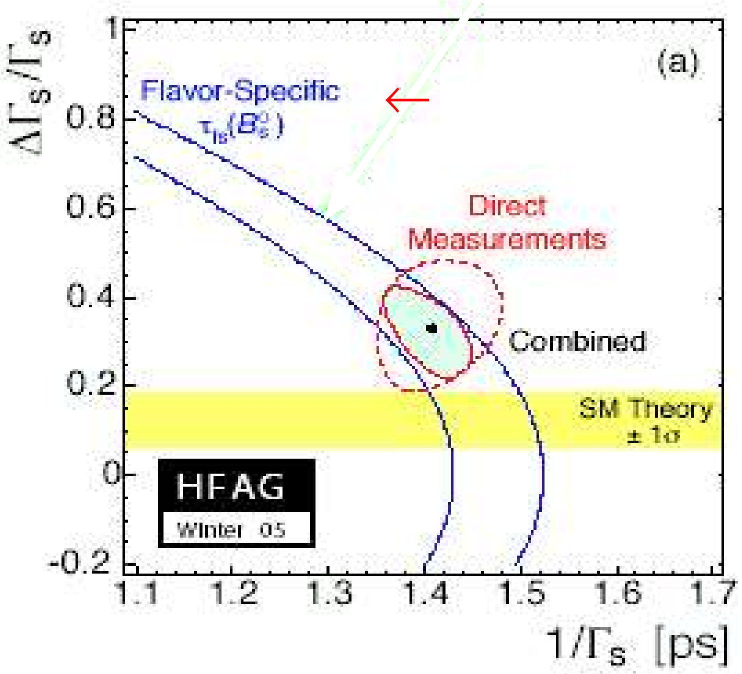
$$\Delta\Gamma_s/\Gamma_s = 0.33^{+0.09}_{-0.11}$$

3σ effect!!

Summary

At the Tevatron, studying $B_s \to J/\psi(\to \mu^+\mu^-)\ \phi(\to K^+ K^-)$:

Experiment	$\Delta\Gamma_s/\Gamma_s$	$\bar{\tau}$ (ps)	τ_L (ps)	τ_H (ps)
CDF RunII	$0.65^{+0.25}_{-0.33}$	$1.40^{+0.15}_{-0.13}$	$1.05^{+0.16}_{-0.13}$	$2.07^{+0.58}_{-0.46}$
→ DO RunII	$0.21^{+0.33}_{-0.45}$	$1.39^{+0.15}_{-0.16}$	$1.23^{+0.16}_{-0.13}$	$1.52^{+0.39}_{-0.43}$



$$\bar{\tau} = \frac{1}{\Gamma_s} = 1.405^{+0.043}_{-0.047}\ \text{ps}$$

$$\Delta\Gamma_s/\Gamma_s = 0.33^{+0.09}_{-0.11}$$

HFAG average (using preliminary input)

Prospects

- Currently measurements are dominated by statistics and the systematics are small
  - DØ: three angles analysis soon
  - CDF: update analysis, $\phi\phi$, ϕK^*, KK (difficult) $D_s D_s$ (tiny)
- Since flavor specific provide an excellent constraint, having a precise lifetime measurement (of semi-leptonic, for instance) is very important
- Of course in a not clean environment like p-pbar the big problem is the trigger
  - DØ: Layer 0 inside current silicon improve $\sigma(c\tau)$, silicon track trigger, and DAQ – improve bandwidth
  - CDF: upgrade track trigger, and DAQ