B_s Mixing and Lifetime Difference Measurements

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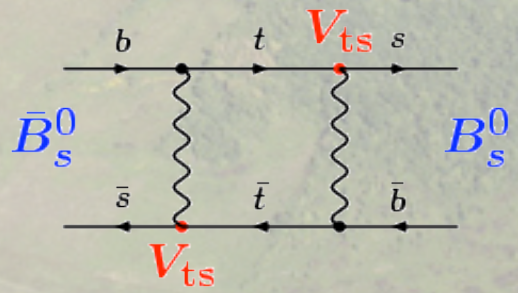
For the DØ and CDF Collaborations

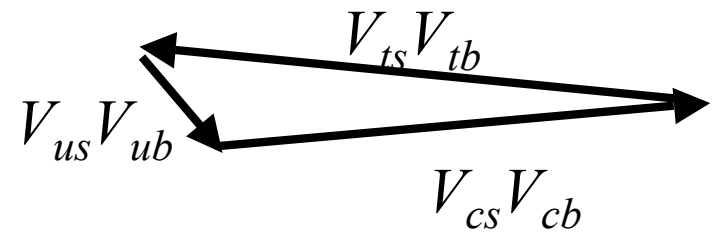


April, 17 2007
DIS 2007 Conference

Mixing and CP Violation

- Standard model: mass ≠ weak eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

  - 3 generations provides for CP violation

$$Mag(\mathrm{CPV}) \approx f(m^2_j - m^2_i) \times f(\theta_{ij}) \times \sin\phi_{CP}$$

  - Small value of CP phase expected:
    - Can't explain N_b excess

$$\phi_s = 4.2 \pm 1.4 \times 10^{-3}$$

A. Lenz, U. Nierste hep-ph/0612167

- Mesons are ideal for studying CPV
  - matter – antimatter bound state
  - Neutral mesons: continuously transforming between matter and antimatter states

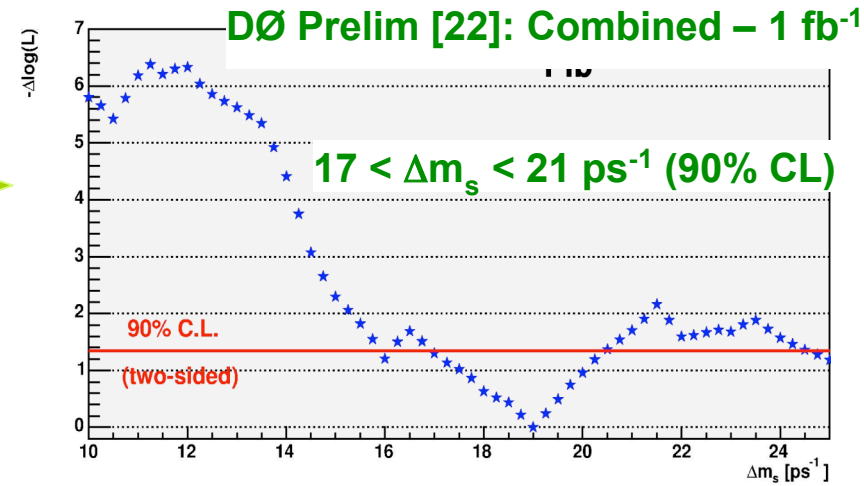
$$i\frac{\partial}{\partial t}\begin{vmatrix} M(t) \\ \overline{M}(t) \end{vmatrix}\rangle = \begin{pmatrix} m_{11} - i\frac{\Gamma_{11}}{2} & m_{12}e^{-i\phi} - i\frac{\Gamma_{12}}{2} \\ m_{21}e^{i\phi} - i\frac{\Gamma_{21}}{2} & m_{11} - i\frac{\Gamma_{11}}{2} \end{pmatrix}\begin{vmatrix} M(t) \\ \overline{M}(t) \end{vmatrix}\rangle$$

Measurements in B_s System

- ΔM_s
  - Thru box diagrams: sensitive to new physics
  - D0: $B_s \to D_s l \nu$

    D0 Collab. PRL 97 021802 (2006)

  ❖ CDF: $B_s \to D_s l \nu$; $B_s \to D_s \pi X$



- $\Delta\Gamma$
  - Tree level, not sensitive to new physics
  - Defines how see CPV

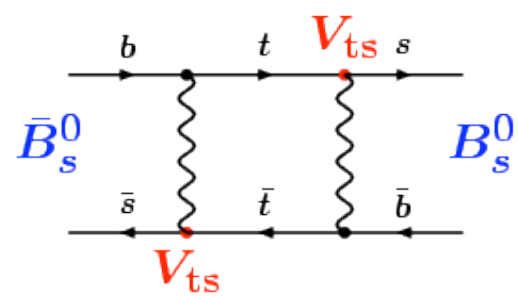
  ❖ $B_s \to D_s D_s$(D0); $J/\psi\phi$, KK

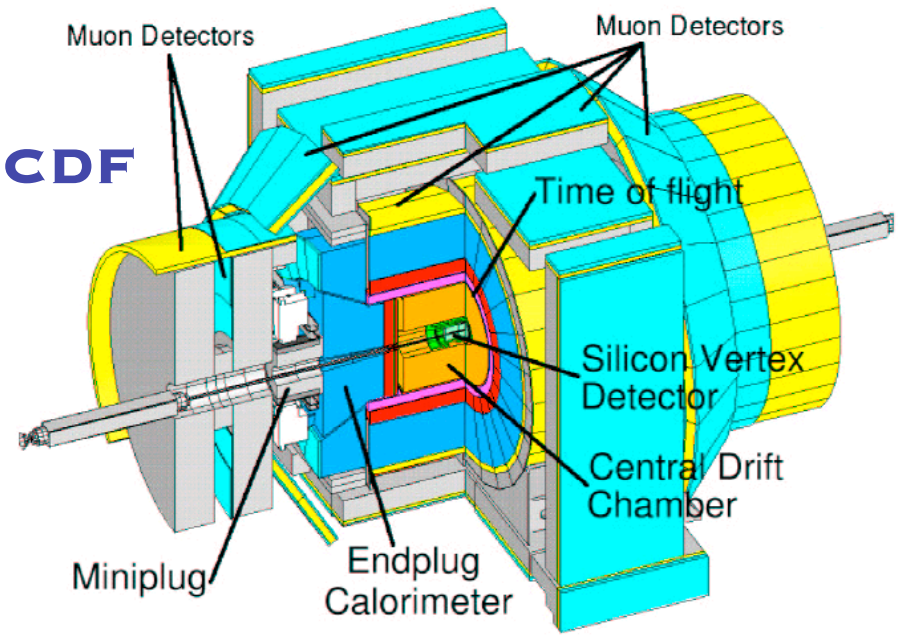
- ϕ_s
  - Also loops: sensitive to new CP effects

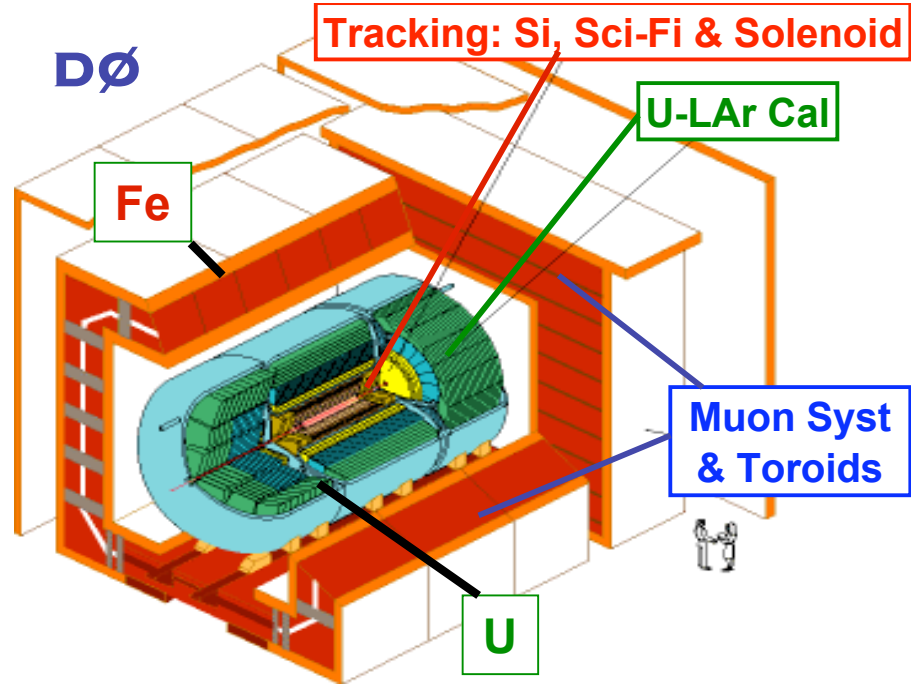
    ϕ_s = -0.5 – -0.8 in 4-gen models

    Hou, Nagashima, Soddu; hep-ph/0610385

  ❖ $B_s \to J/\psi\ \phi$, combination (D0)







Data Samples

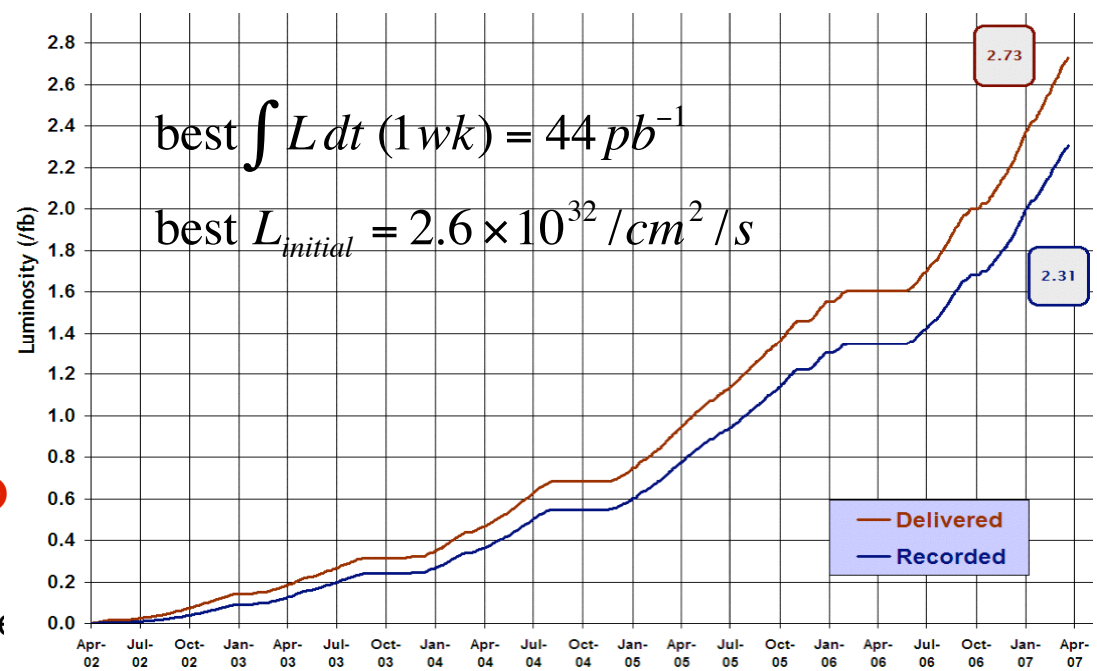
>2.7 fb^{-1} delivered

>2.3 fb^{-1} recorded

up to 1.3 fb^{-1} results

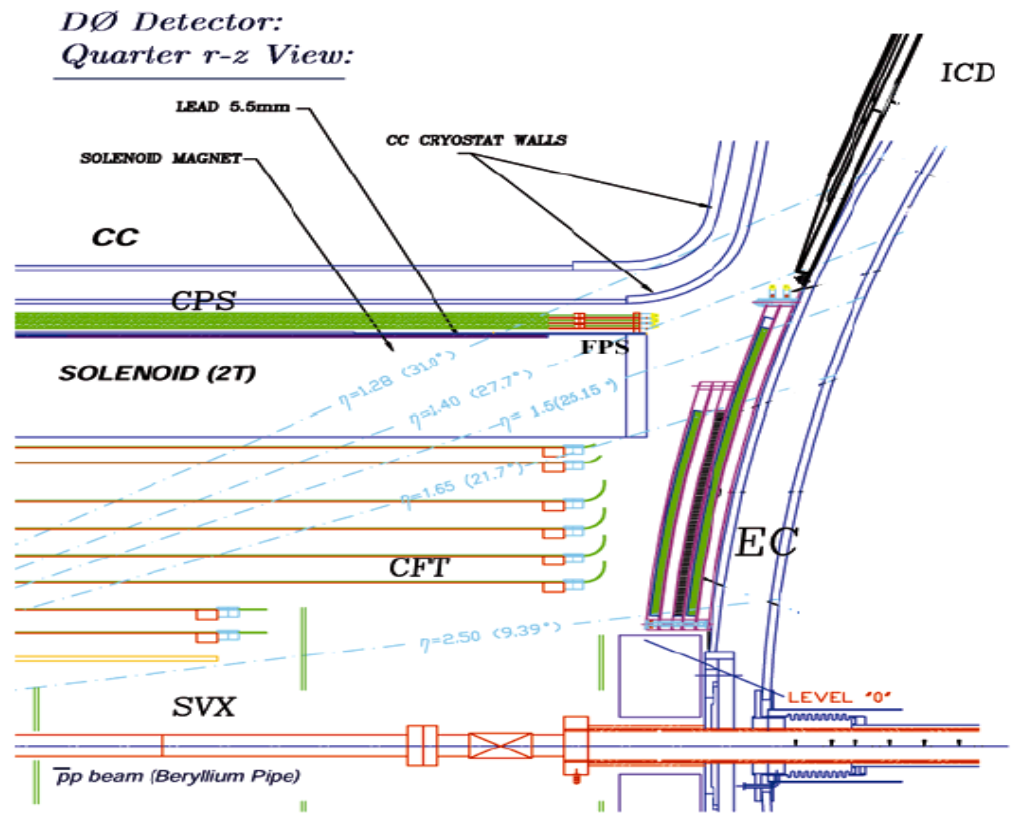
Production	**B-Factories**	**Tevatron**
	Υ(5S)	**(in accept)**
Approx B_s Rate	**1 Hz**	**600 Hz**

R. K



Track and Muon Detection

Important at the Tevatron
- Triggering • Muons
- Tracking/Vertexing • (π / *K Separation*)



Trigger	CDF	DØ
2-Track	P_T(trk)>2.0 GeV $0.12<d_0<1$ mm ΣP_T>5.5 GeV	—
l + Displ Trk	P_t^l>4, P_t^{trk}>2 GeV $0.12<d_0<1$ mm	—
1-Muon	—	P_T>3,4,5 GeV or P_T>5 GeV & $d_0/\sigma(d_0)$>3 (luminosity dependent)
2-Muon	$P_T(\mu's)$>1.5 GeV	$P_T(\mu's)$>2.0 GeV

Muons	Coverage	Shielding
DØ	$\lvert\eta\rvert < 2.0$	12-18 λ_I
CDF	$\lvert\eta\rvert < 1.0$	>5 λ_I

Measuring Δm_s

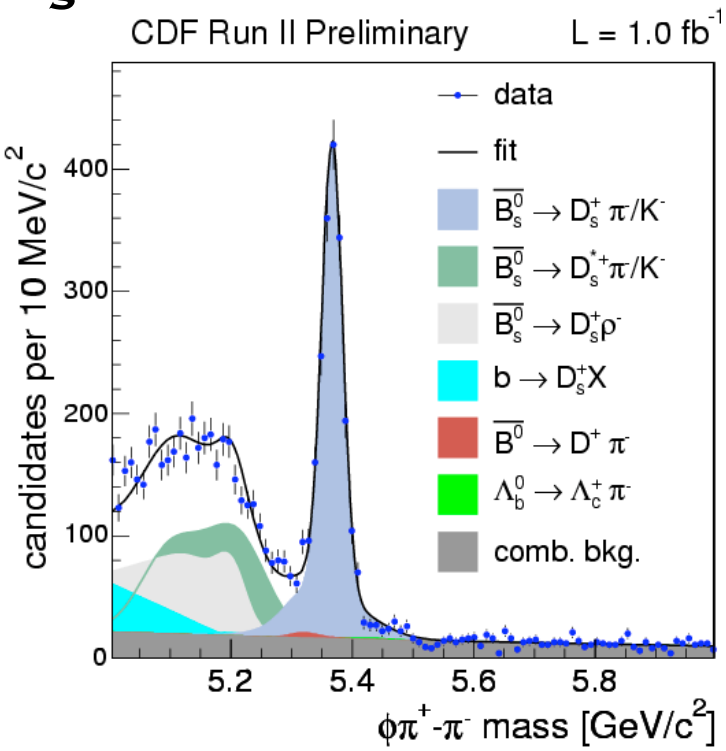
- Channels
  - Semileptonic:

$$\overline{B}_s^0 \rightarrow D_s^{(*)+} l^- \overline{\nu}_e \quad (l = e, \mu)$$

  - Hadronic:

$$\overline{B}_s^0 \rightarrow D_s^{(*)+} \pi^-, D_s^+ \pi^- \pi^+ \pi^-, D_s^+ \rho^-$$

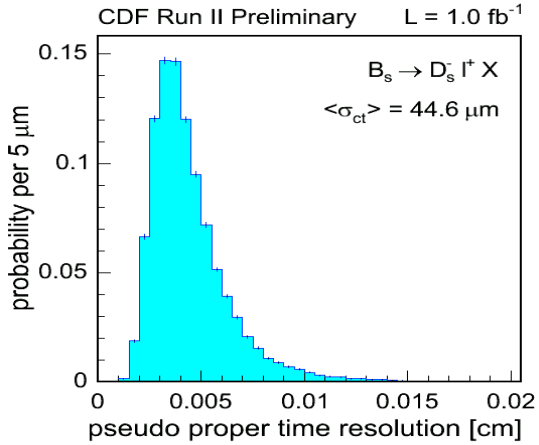
- same-side and opposite-side tagging
  - Opposite-side
    - Lepton, jet, K charge → ANN
  - Same-side
    - Use K identification likelihood and kinematics → ANN

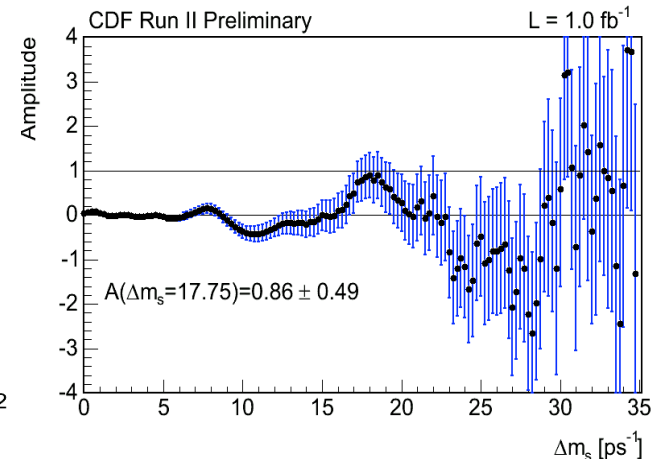


- Samples
  - Fully reconstructed hadronic: 5600
  - Partially reconstructed hadronic: 3100
  - Partially reconstructed semileptonic: 61500

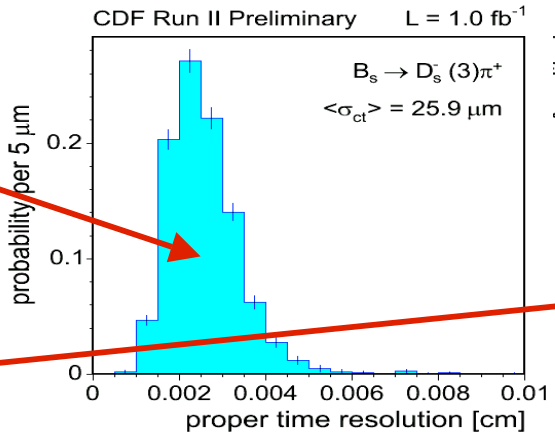
Amplitude Scan

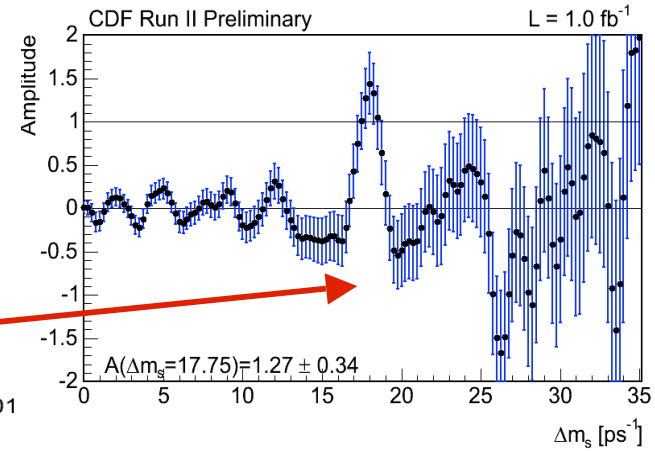
- Semileptonic channel



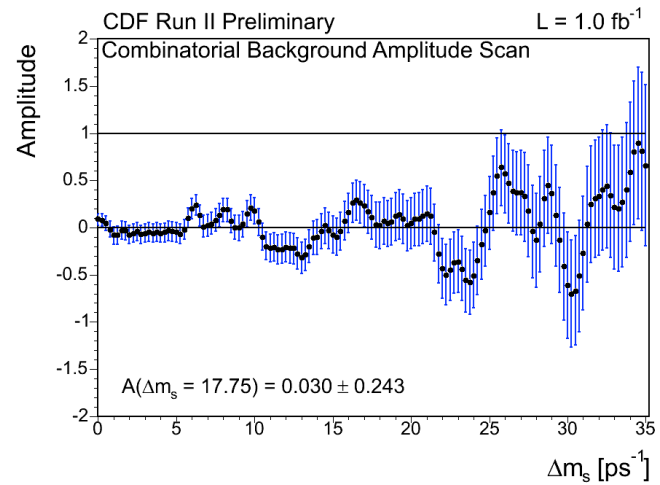


- Hadronic channel
  - Superior decay time resolution gives excellent sensitivity at values of ΔM_s ~20 ps^{-1}

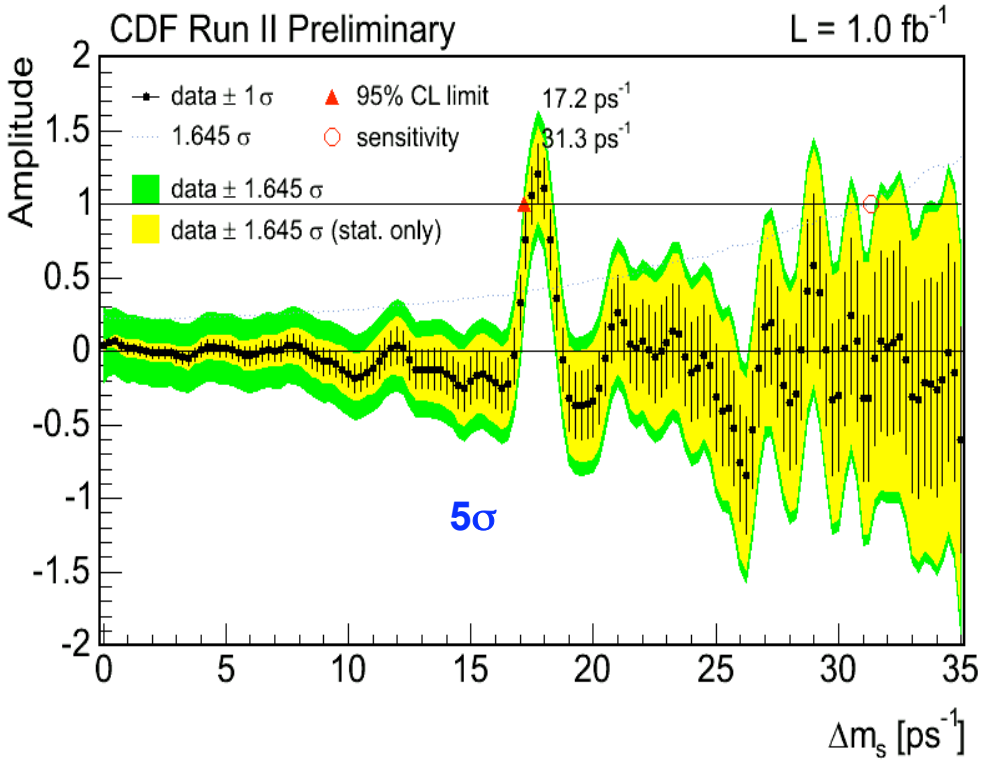


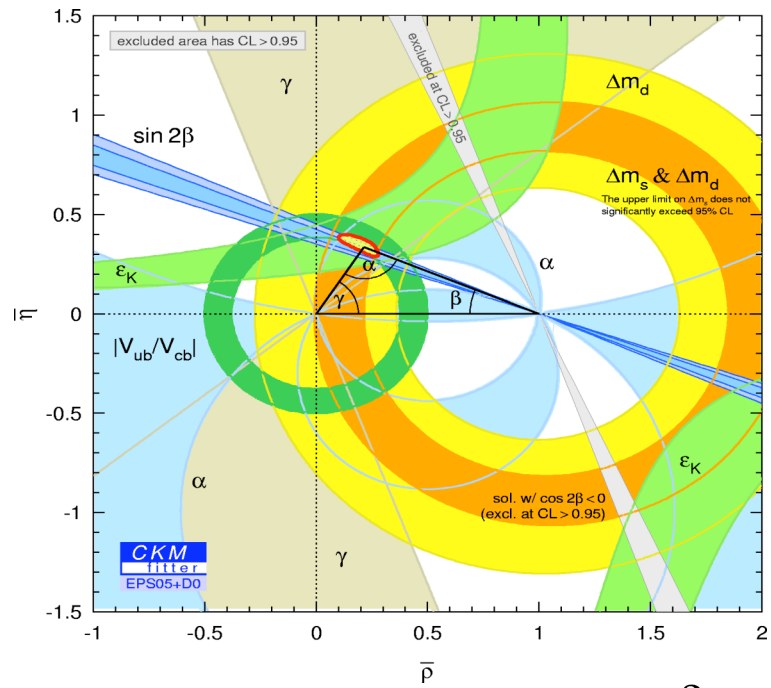


- Combinatorial background



Precision Measurement of Δm_s





$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}

CDF Collab. PRL 97 062003 (2006)

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.2060 \pm 0.007\,(\text{exp})^{+0.0081}_{-0.0060}\,(\text{theo})$$

Measurement of $\Delta\Gamma$: $B_s \to D_s^{(*)} D_s^{(*)}$

- $\Delta\Gamma = \Gamma_L - \Gamma_H = \Gamma_{CP+} - \Gamma_{CP-}$
  - Determine assuming SM level CPV in B_s mixing: $\cos\phi_s \equiv 1$

- Consider $B_s \to D_s^{(*)} D_s^{(*)}$
  - $D_s D_s$ (PP), $D_s^* D_s$ (VP), $D_s^* D_s^*$ (VV)

$$2BR(B_s \to D_s^{(*)} D_s^{(*)}) \approx \left(\frac{\Delta\Gamma_s^{CP}}{\Gamma_s}\right)\left(1 + O\left(\frac{\Delta\Gamma_s}{\Gamma_s}\right)\right)$$

- Heavy quark limit + factorization
  - $B_s^{odd} \to D_s^* D_s$ forbidden

- $D_s^* D_s^*$ in S-wave
  $\Rightarrow$ $Ds^{(*)} Ds^{(*)}$ pure CP even

- Expectations of 5% odd R. Alexan et al., PLB 316, 567 (1993)
  - Others suggest up to 30% odd

$B_s \to D_s^{(*)} D_s^{(*)}$ Decay

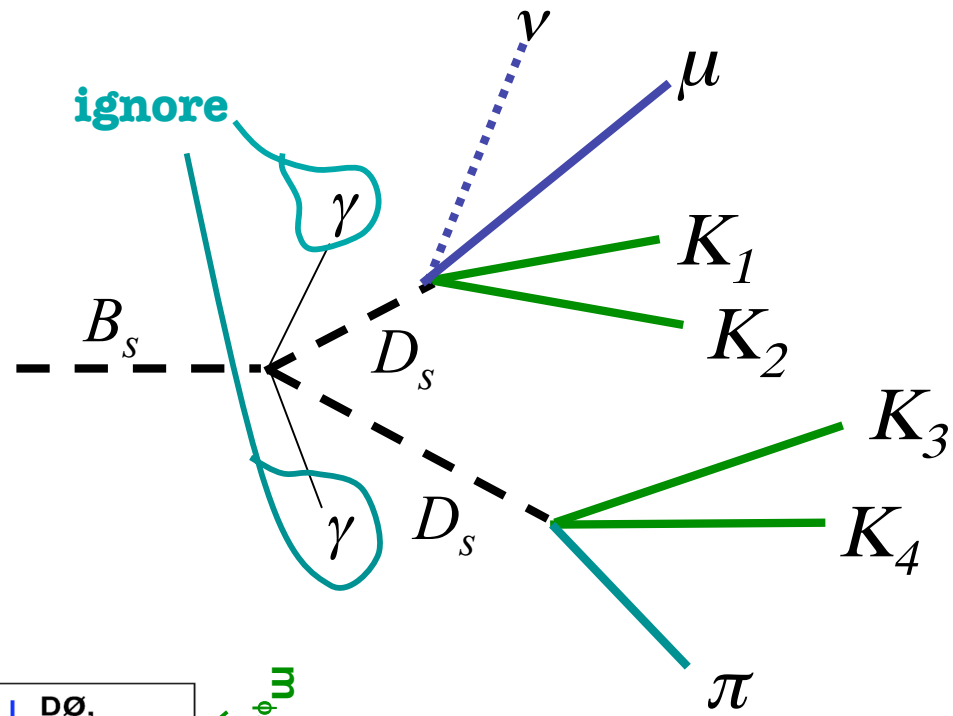
$B_s^0 \to D_s^{(*)} D_s^{(*)}$

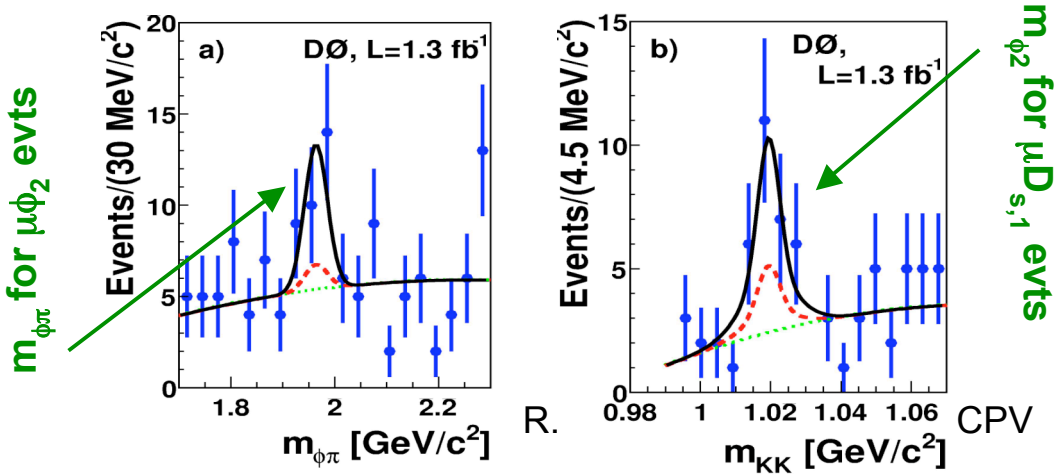
$D_{s1} \to \phi_1 \pi^+ ; \phi_1 \to K^+ K^-$

$D_{s2} \to \phi_2 \mu^- \nu ; \phi_2 \to K^+ K^-$

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

- Look for correlated production of $D_s \to \phi\pi$ and $D_s \to \phi\mu$
- Trigger on muon from semileptonic D_s decay





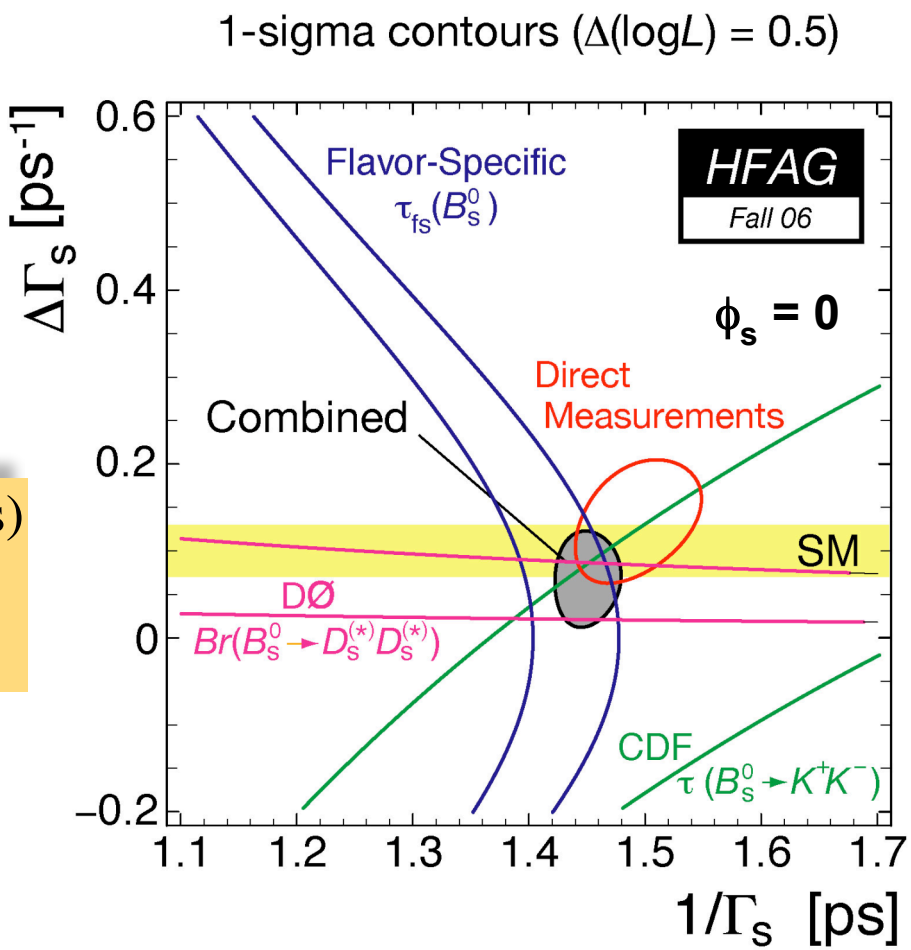
$$N(D_s^{(*)} D_s^{(*)}) = 13.4^{+6.6}_{-6.0}$$

BR($B_s \to D_s^{(*)} D_s^{(*)}$) and $\Delta\Gamma_s$

$$R = \frac{BR(B_s \to D_s^{(*)} D_s^{(*)}) BR(D_s \to \phi\mu\nu)}{BR(B_s \to \mu\nu D_s^{(*)})}$$
$$= 0.015 \pm 0.007\,(\text{stat})$$

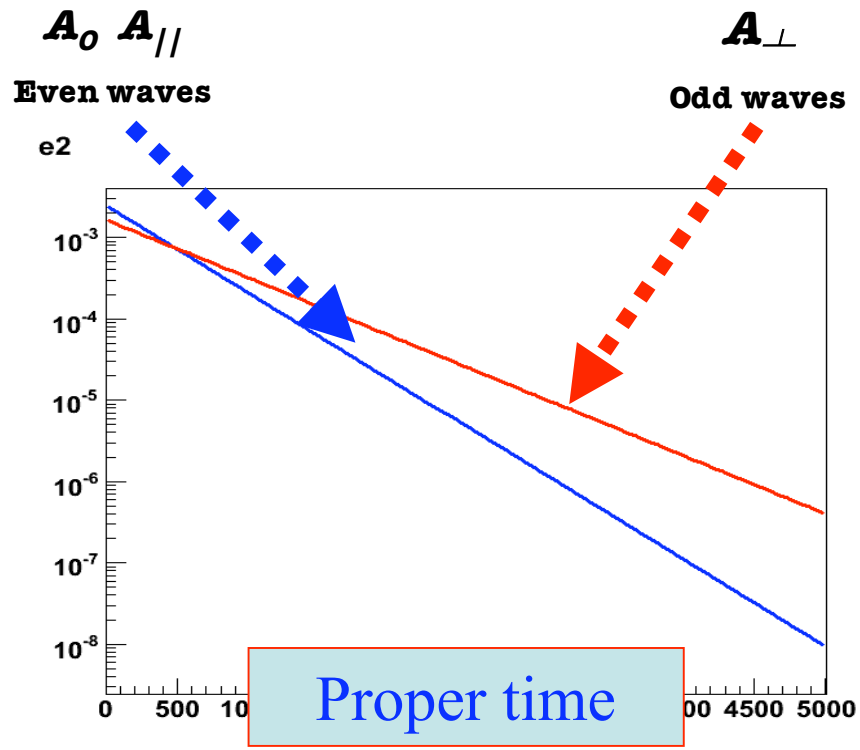
$$BR(B_s \to D_s^{(*)} D_s^{(*)}) = 0.039^{+0.019}_{-0.017}(\text{stat})^{+0.016}_{-0.017}(\text{sys})$$
$$\frac{\Delta\Gamma_{CP}}{\Gamma} = 0.079^{+0.038}_{-0.035}(\text{stat})^{+0.031}_{-0.030}(\text{sys})$$

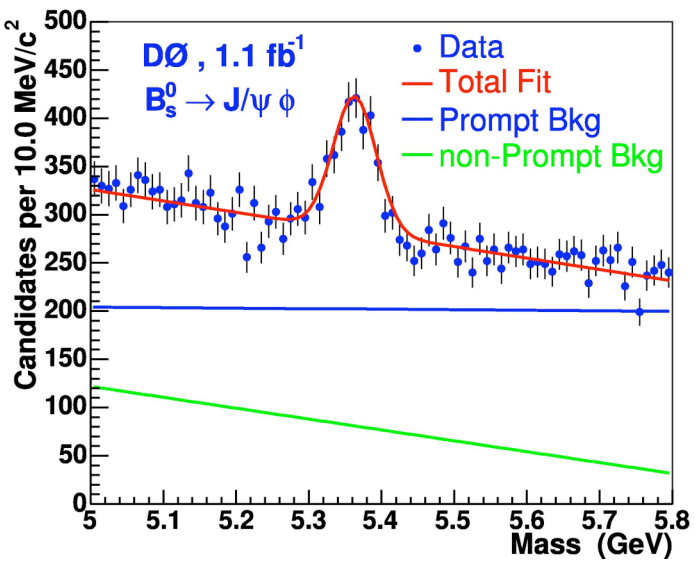
DØ Collab. hep-ex/0702049, subm. to PRL



$B_s \rightarrow J/\psi\ \phi$

- $b \rightarrow c\bar{c}\ s \rightarrow$ CP even and CP odd final states
  - Separate with time-dependent angular distributions
    - measurement of lifetime difference
  - Large lifetime difference: can extract mixing phase



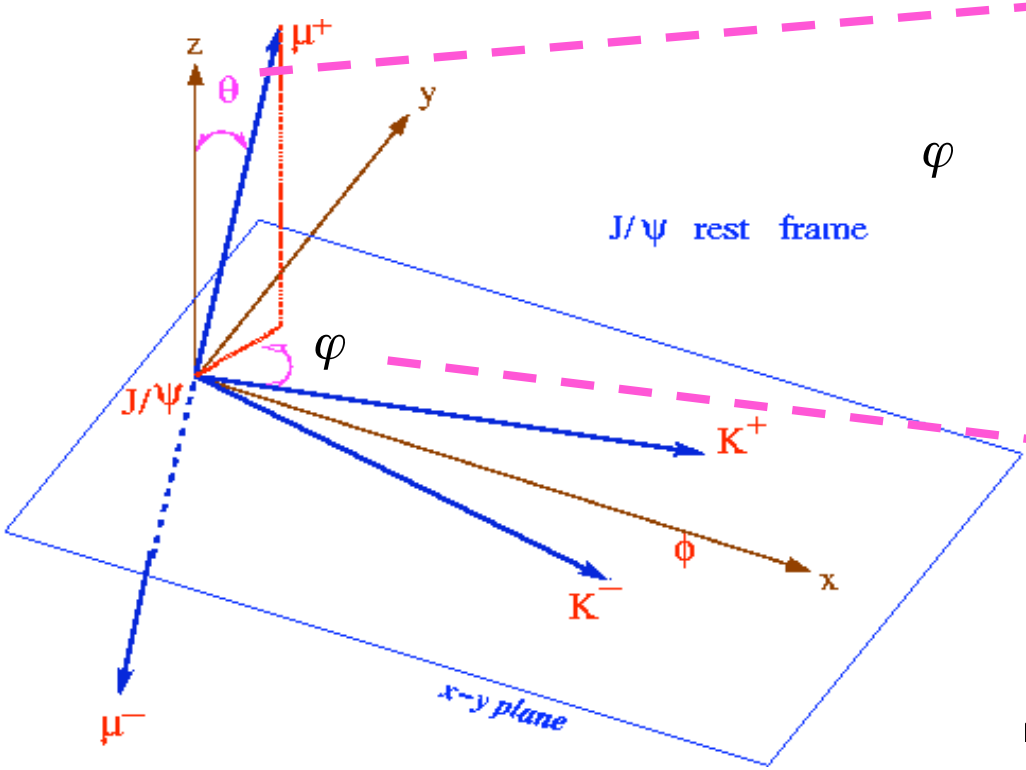


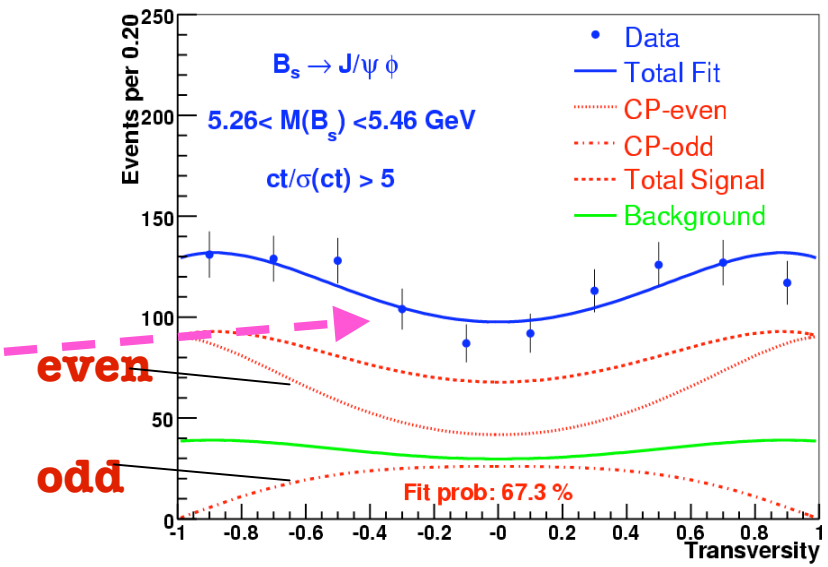
1039±45 B_s signal candidates

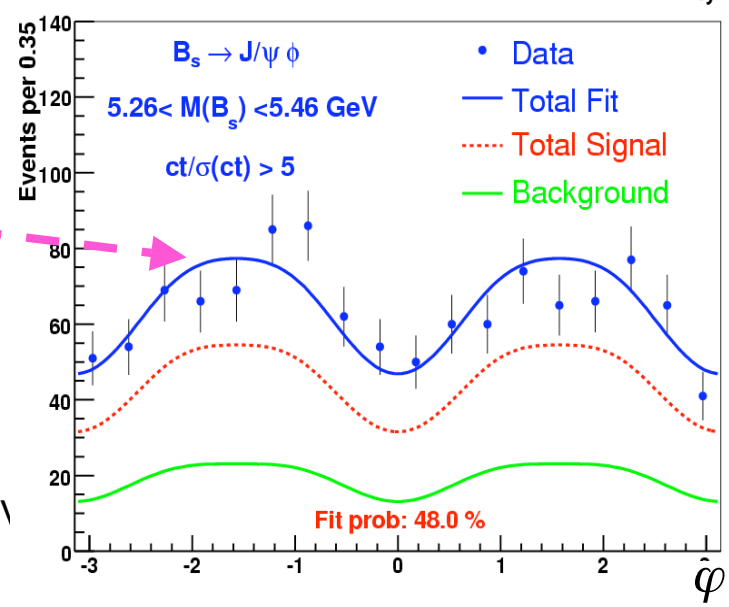
Decay Angle Fit

- signal, prompt and non-prompt BG
  - Decay angles: θ, φ and ψ

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

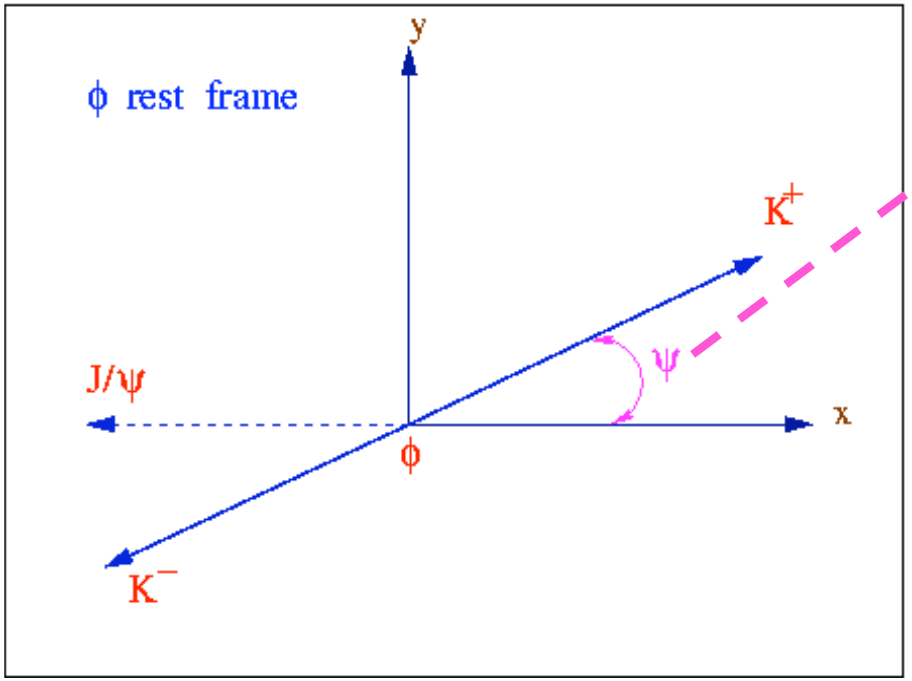


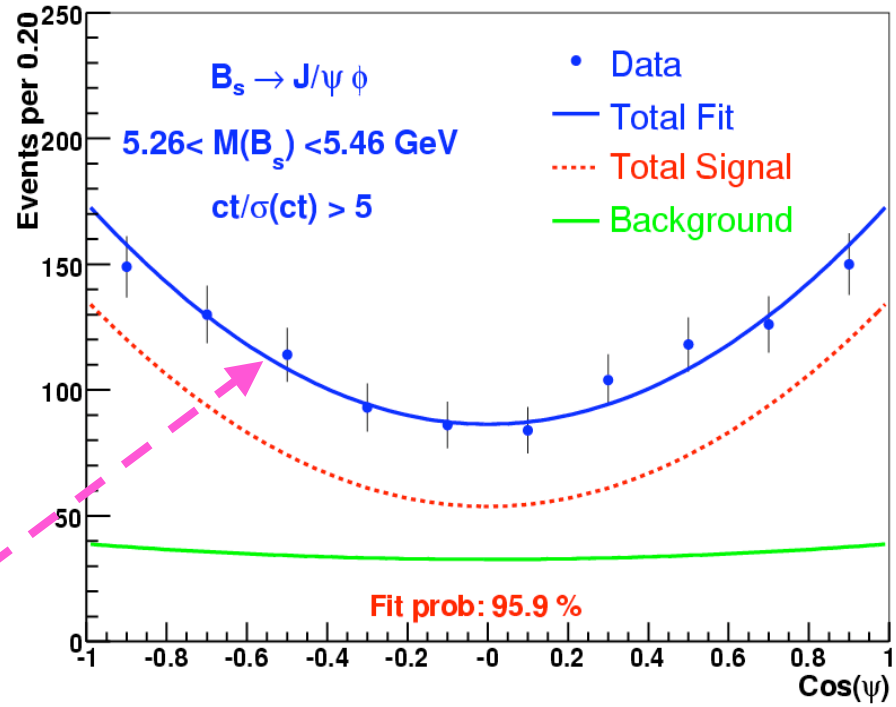


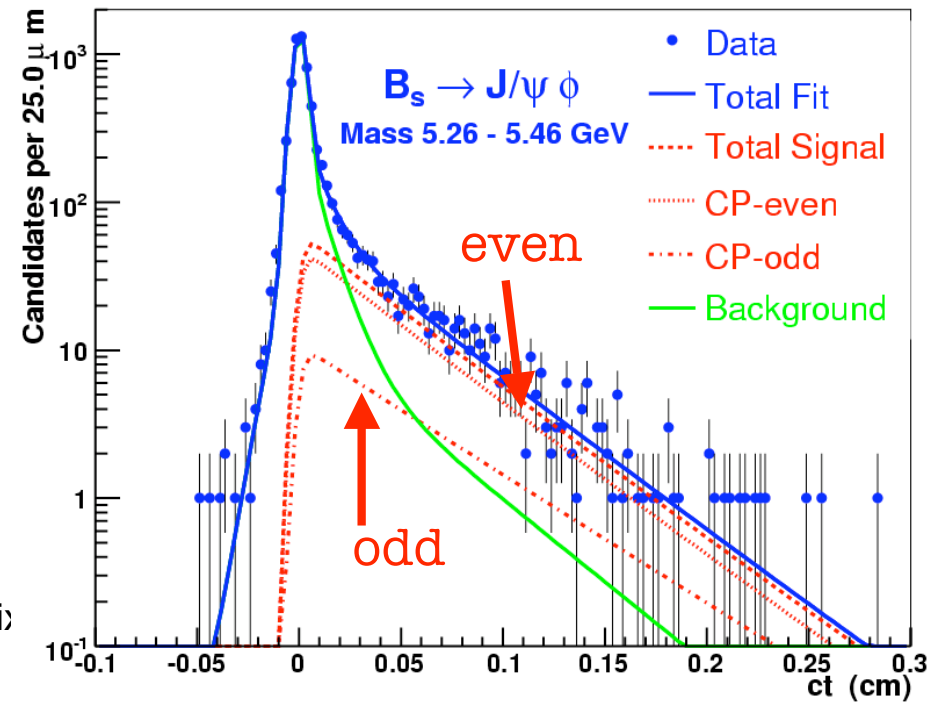


ıd CP\

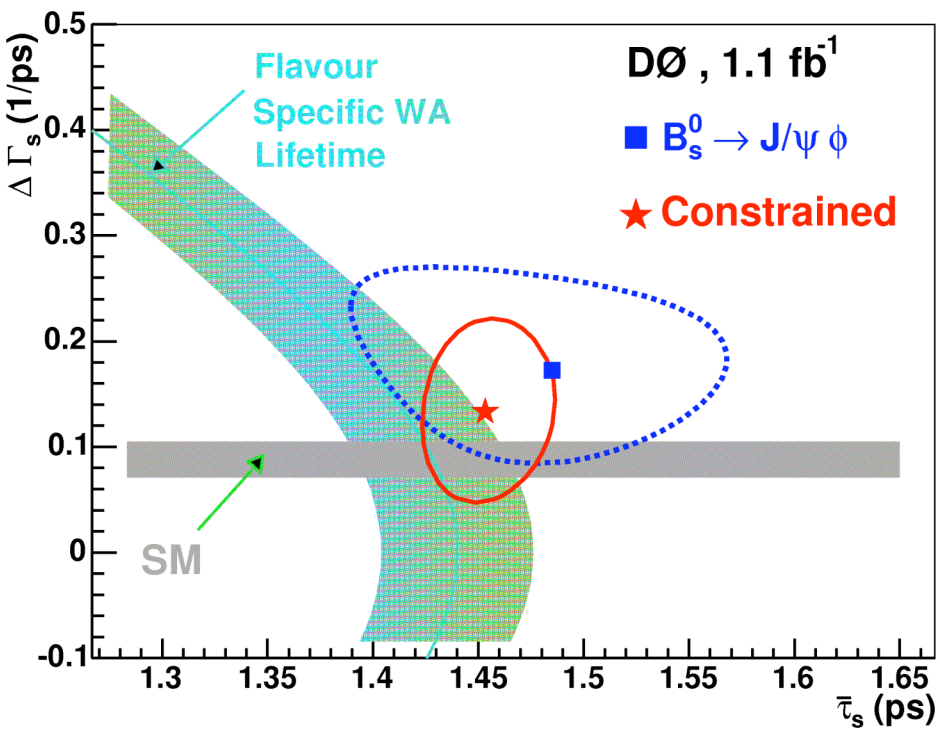
Fit Results

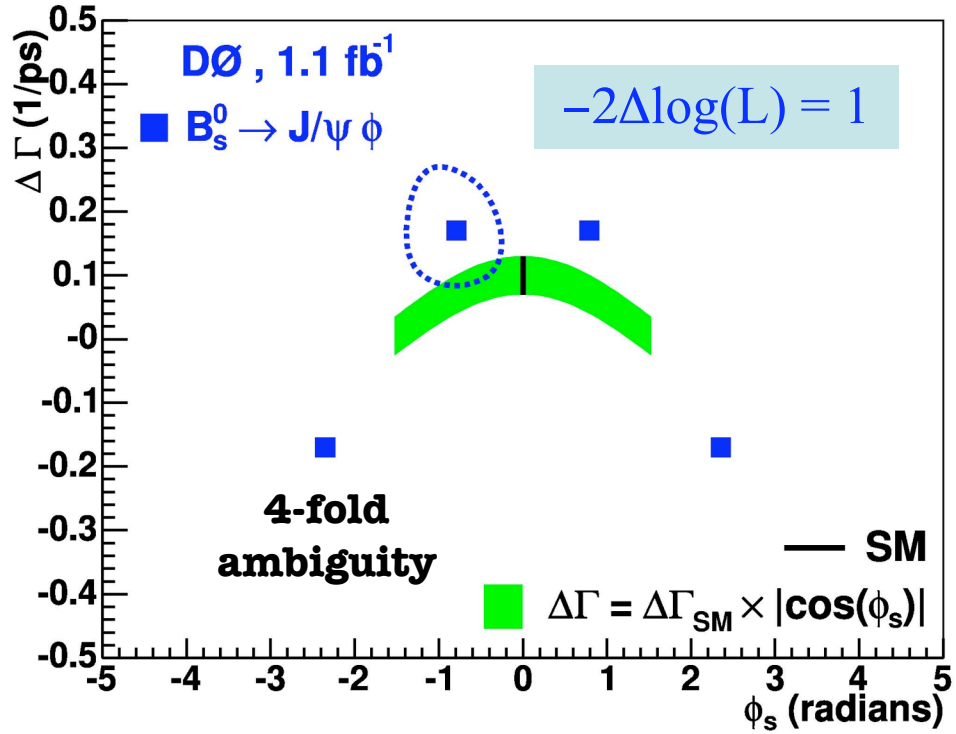

φ rest frame
y
x
K+
K−
J/ψ
ψ
φ


Events per 0.20
Bs → J/ψ φ
5.26< M(Bs) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
Total Signal
Background
Fit prob: 95.9 %
Cos(ψ)


Candidates per 25.0 μ m
Bs → J/ψ φ
Mass 5.26 - 5.46 GeV
Data
Total Fit
Total Signal
CP-even
CP-odd
Background
even
odd
ct (cm)

Direct Measurement of ϕ_s





$$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.02\, ps^{-1}$$

$$\phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01}$$

DØ Collab. hep-ex/0701012 submitted to PRL

Tying It All Together

- Several additional measurements provide information to further constrain the CP phase
- Flavor-specific lifetime of B_s mesons

$$\Gamma_{fs} = \overline{\Gamma}_s - (\Delta\Gamma_s)^2/2\overline{\Gamma}_s + O(\Delta\Gamma_s)^3/\overline{\Gamma}_s$$

$$\tau_{fs} = 1/\Gamma_{fs} = 1.440 \pm 0.036 \text{ ps} \quad \text{(world avg.)}$$

  - Which includes D0 meas.

$$\tau_{fs} = 1.398 \pm 0.044 \text{ (stat)} \; {}^{+0.028}_{-0.025} \text{(sys) ps}$$

D0 Collab. PRL 97, 241801 (2006)

- Semileptonic charge asymmetry
  - induced by B mixing

$$A_{SL}^{q} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

  - same-sign dimuon charge asymmetry

$$A_{SL}^{d} + \frac{f_s Z_s}{f_d Z_d} A_{SL}^{s} = -0.0092 \pm 0.0044 \text{ (stat)} \pm 0.0032 \text{ (sys)}$$

D0 Collab. PRD 94, 092001 (2006)

  - Using B-factory value of A^d_{SL}, get

$$A_{SL}^{s} = -0.0064 \pm 0.0101$$

Combination Analysis

- Direct asymmetry measurement: $B_s \to \mu\nu D_s$, $D_s \to \phi\pi$

$$A_{SL}^s = +0.0245 \pm 0.0193(\text{stat}) \pm 0.0035(\text{sys})$$

DØ Collab., subm. to PRL, hep-ex/0701007

  - nearly independent of dimuon-based measurement

$$A_{SL}^s = 0.0001 \pm 0.0090$$

- Use CDF $\Delta M_s = 17.8 \pm 0.1\ \text{ps}^{-1}$

$$\Delta\Gamma_s \tan\phi_s = A_{SL}^s \Delta M_s = 0.02 \pm 0.16\ \text{ps}^{-1}$$

- Refit $B_s \to J/\psi\,\phi$ data using $\Delta\Gamma_s \tan\phi_s$ and τ_{fs} as constraints

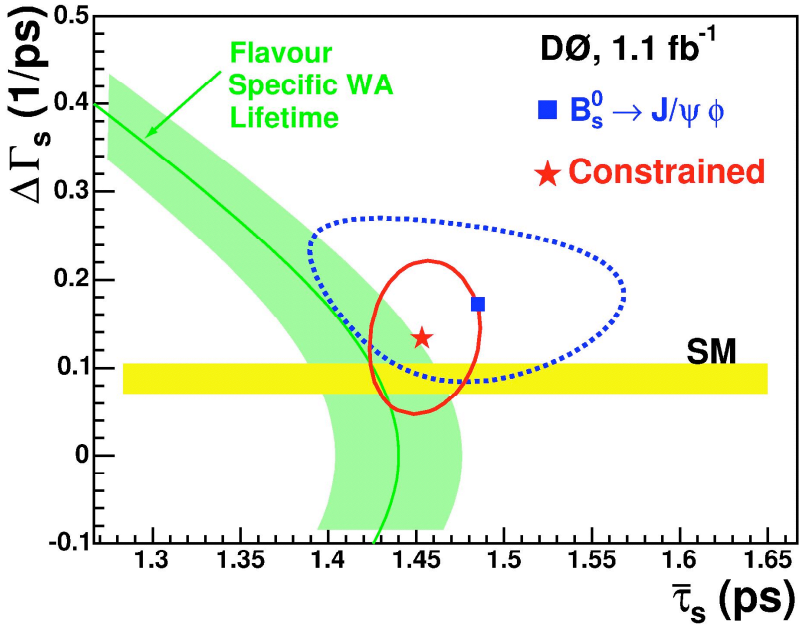
$\phi_s < 0$, $\cos\delta_1 > 0$, $\cos\delta_2 < 0$ choice

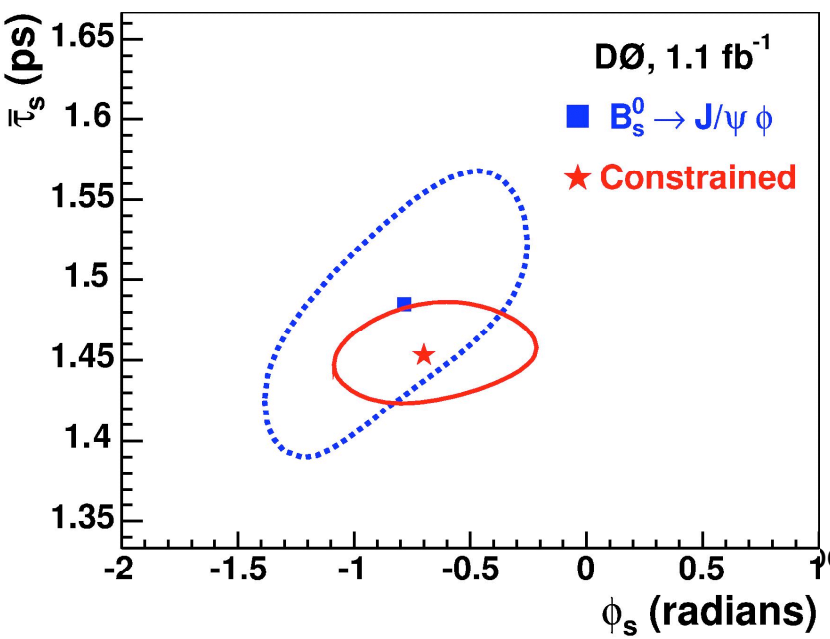
$$\Delta\Gamma_s = 0.13 \pm 0.09\ \text{ps}^{-1}$$

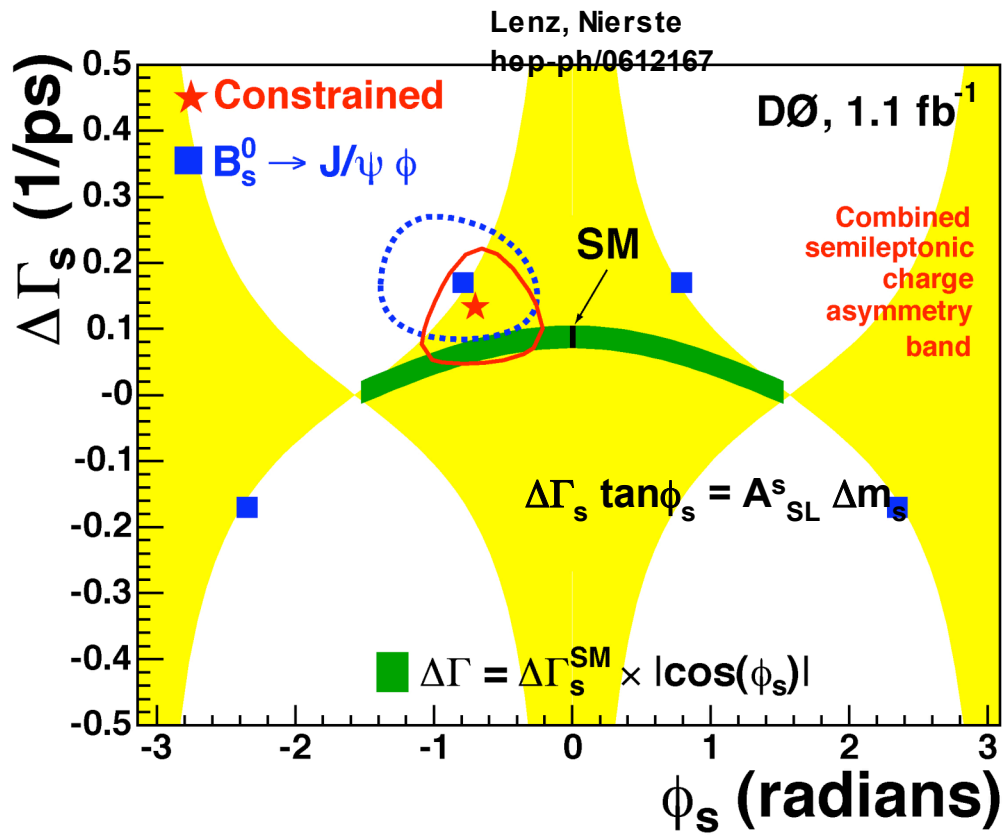
$$\phi_s = -0.70^{+0.47}_{-0.39}$$

	SM Pred
$\Delta\Gamma_s$	$0.088 \pm 0.017\ \text{ps}^{-1}$
ϕ_s	$(4.2 \pm 1.4) \times 10^{-3}$

Results from Combination







Final Notes

- B_s physics at Tevatron has been quite productive
  - New measurements of several key parameters:

$$\Delta M_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{sys})\,\text{ps}^{-1}$$

$$|V_{td}/V_{ts}| = 0.2060 \pm 0.007\,(\text{exp})^{+0.0081}_{-0.0060}\,(\text{theo})$$

$$\Delta\Gamma_s = 0.13 \pm 0.09\ \text{ps}^{-1}$$

$$\phi_s = -0.70^{+0.47}_{-0.39}$$

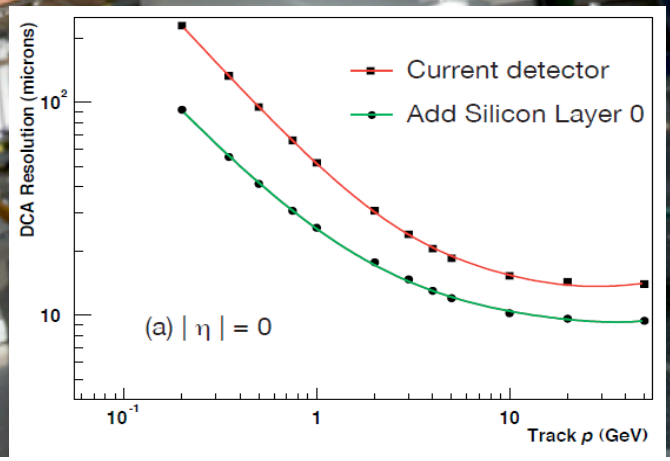
- Tevatron prognosis:
  - Since April '06 upgrade, *rate* of lum. recorded 1.2 fb^{-1}/yr and growing
  - Records continually being set
  - Expect several fb^{-1} by the end of the run
- B_s physics prospects
  - Do not see evidence for new physics
  - Many new measurements to be updated by both experiments
    - E.g. $\Delta\Gamma$ from CDF, all-hadronic ΔM_s from D0
    - Continued effort to constrain ϕ_s is ongoing

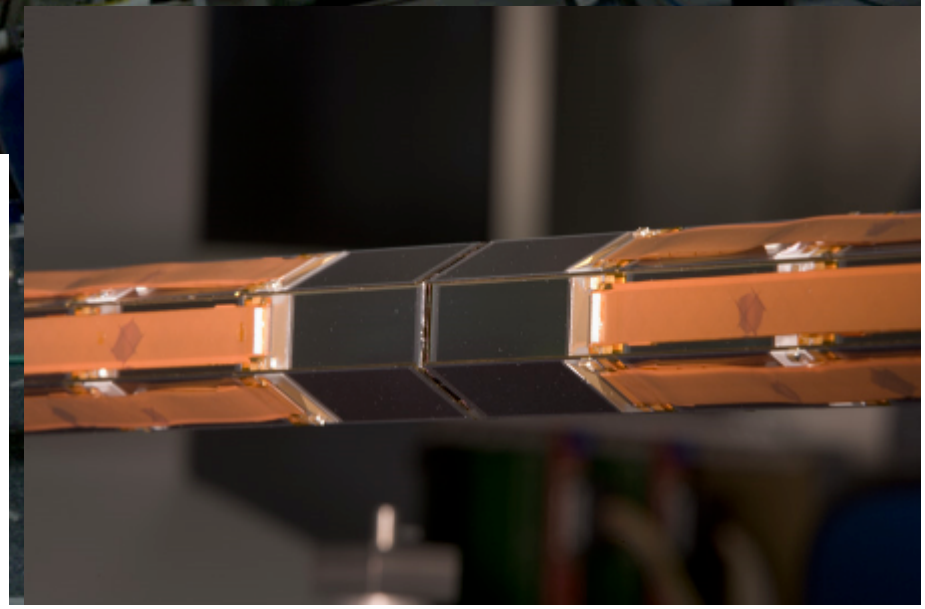
Backup Slides

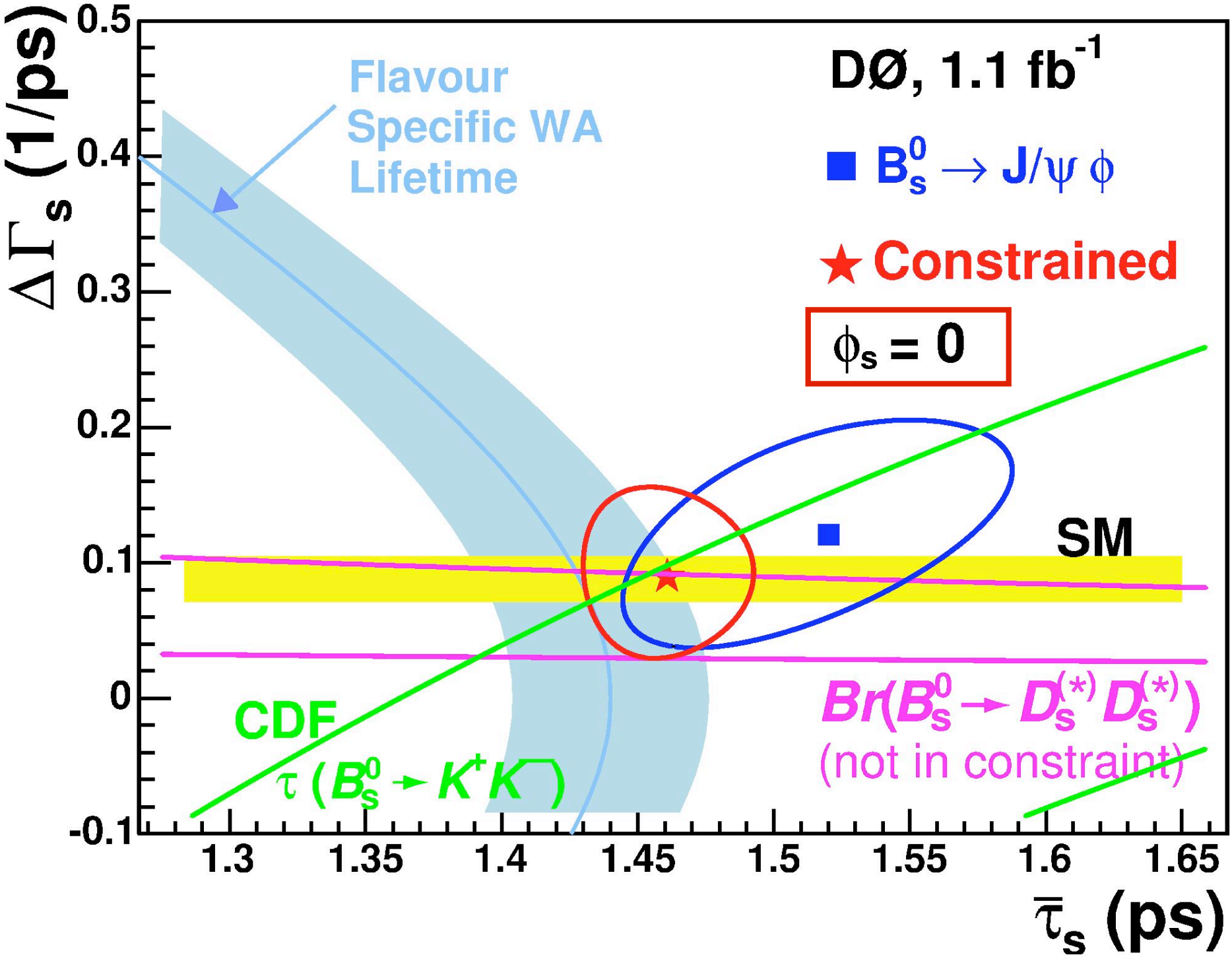
DØ Layer 0 Installation

The detector consists of:

- 48 modules mounted on carbon fiber support structure at 1.7 cm radius
  - 6 f-segments, 8 z-segments
- Four sensor types provide 98.4% of acceptance
  - Sensors 12 and 7 cm lengths






DØ, 1.1 fb^{-1}
Flavour Specific WA Lifetime
$B_s^0 \to J/\psi\,\phi$
Constrained
$\phi_s = 0$
SM
CDF
$\tau\,(B_s^0 \to K^+K^-)$
$Br(B_s^0 \to D_s^{(*)} D_s^{(*)})$
(not in constraint)
$\Delta\Gamma_s$ (1/ps)
$\bar{\tau}_s$ (ps)
0.5
0.4
0.3
0.2
0.1
0
-0.1
1.3
1.35
1.4
1.45
1.5
1.55
1.6
1.65