B_s Lifetime and $\Delta\Gamma_s$ Measurements at DØ

Derek Strom
Northwestern University
For the DØ Collaboration

October 29 – November 3
DPF – Honolulu, Hawaii

*http://www-d0.fnal.gov/~dstrom/DPF06.pdf_*

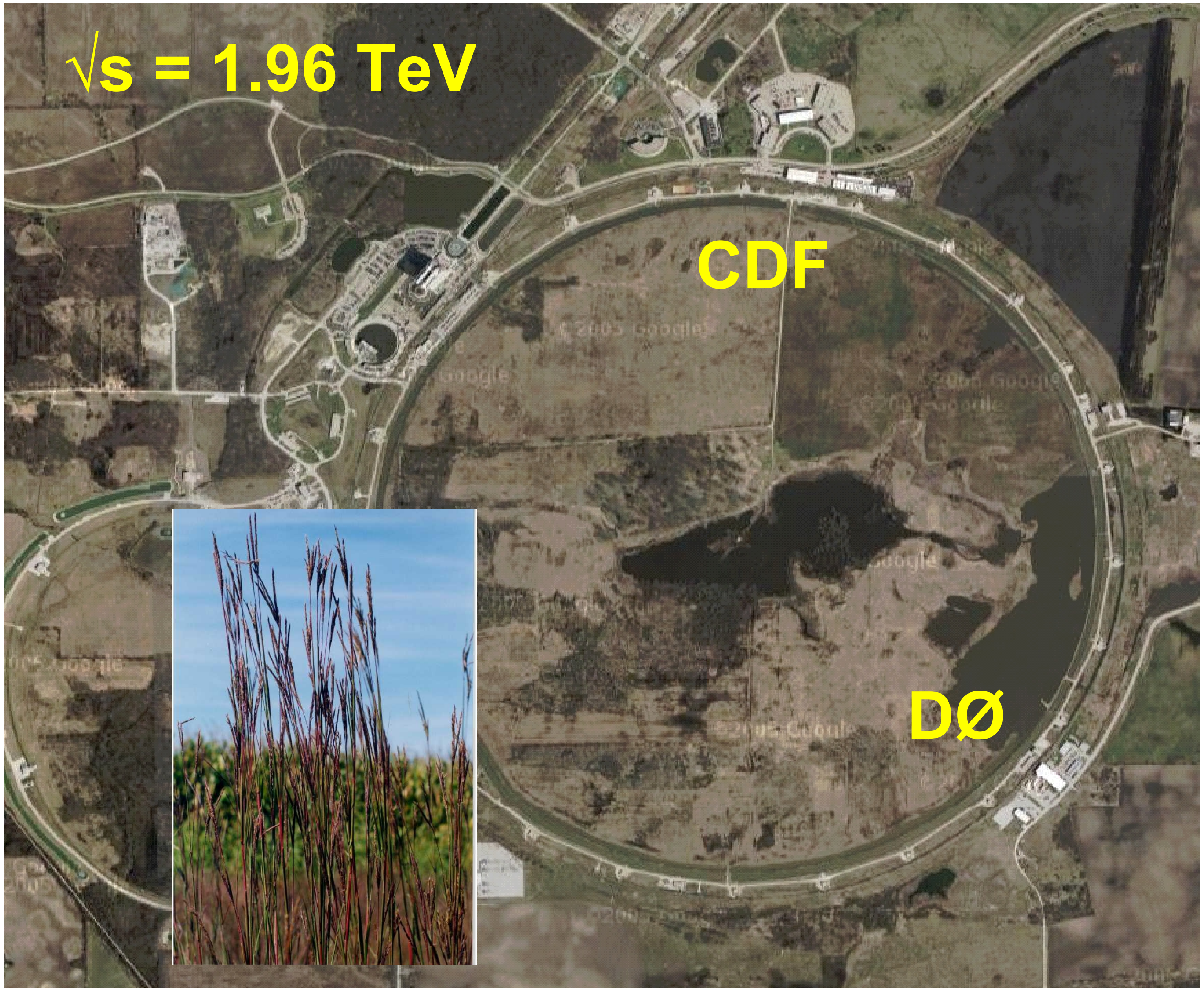
Outline

- B_s Physics Program at DØ
- The DØ Detector
- B_s Lifetime Measurement
- Measurement of $Br(B_s \rightarrow D_s^* D_s^*)$ and $\Delta\Gamma_s$
- Direct Measurement of $\Delta\Gamma_s$ and $\delta\Phi_s$ CPV phase
- Summary

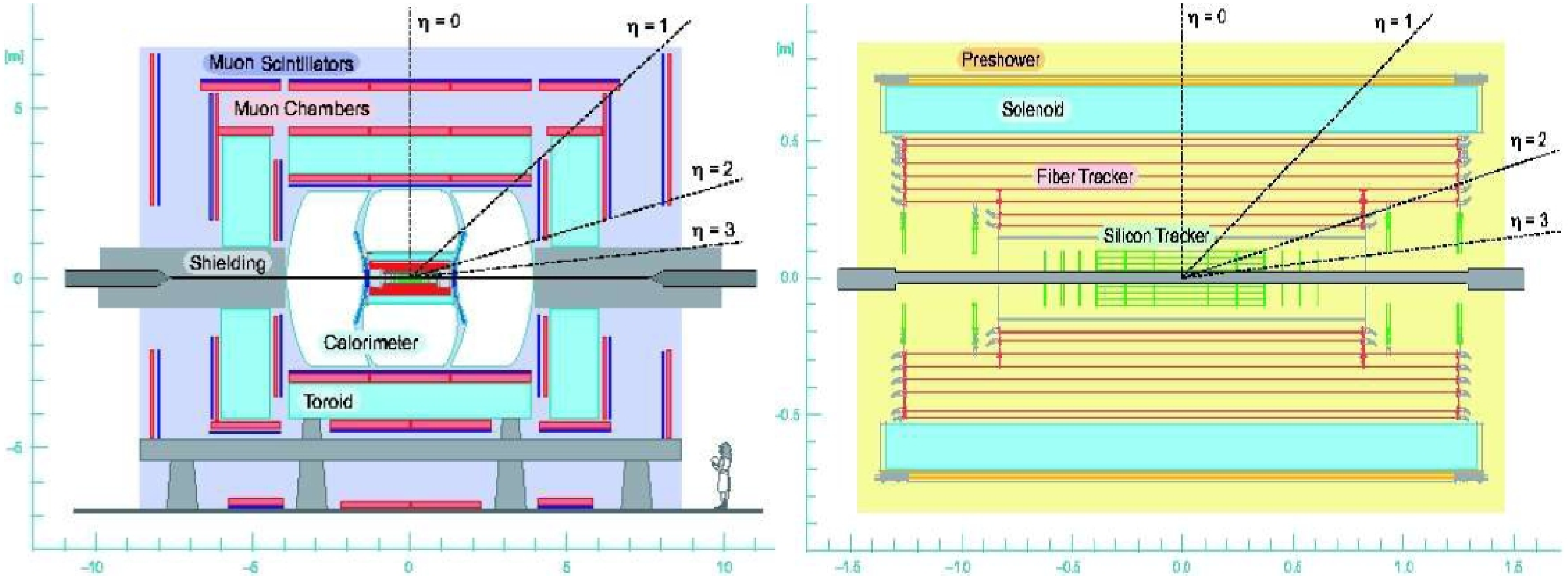
B_s Program @ DØ

- DØ has a rich B physics program.
  - First double-sided bound on B_s mixing parameter, Δm_s.
  - Precision lifetime measurements of B_s, Λ_b, B_c, B^o, B^-.
    - Large boost at Tevatron is good for lifetime studies.
  - $\Delta\Gamma_s$ measurement provides tests SM predictions.
  - $\delta\Phi_s$ measurement tests for CPV and new physics.

DØ Detector



DØ Detector



Tracking (|η| < 3) – Silicon Microstrip Tracker (SMT), Layer0 (RunIIb Upgrade) Silicon Detector, and Central Fiber Tracker (CFT) inside a 2T magnetic field.

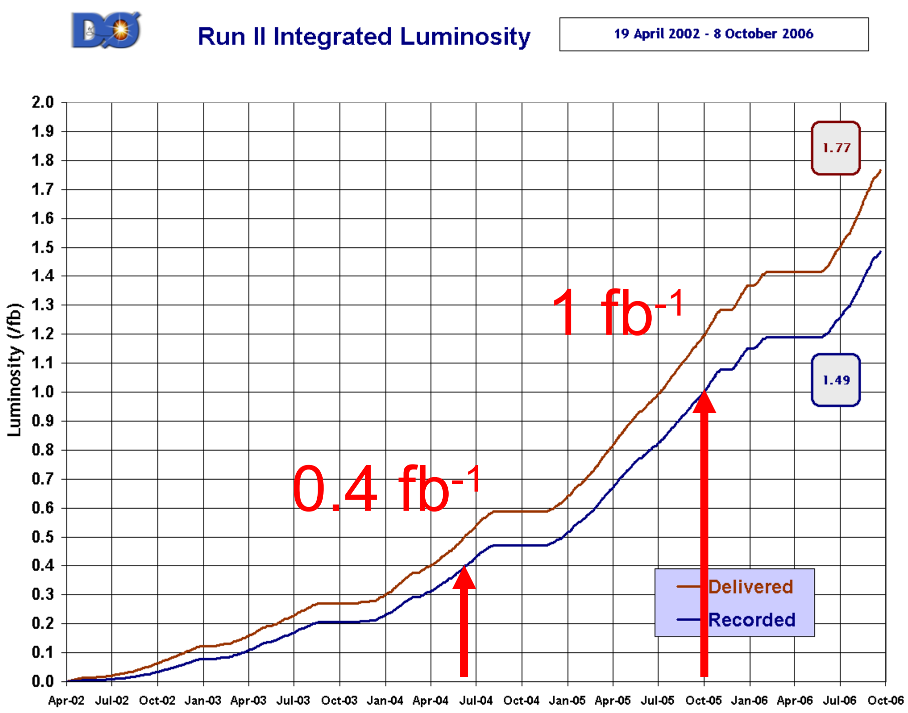
Muon (|η| < 2) – One layer tracking and one layer scintillation trigger counters.

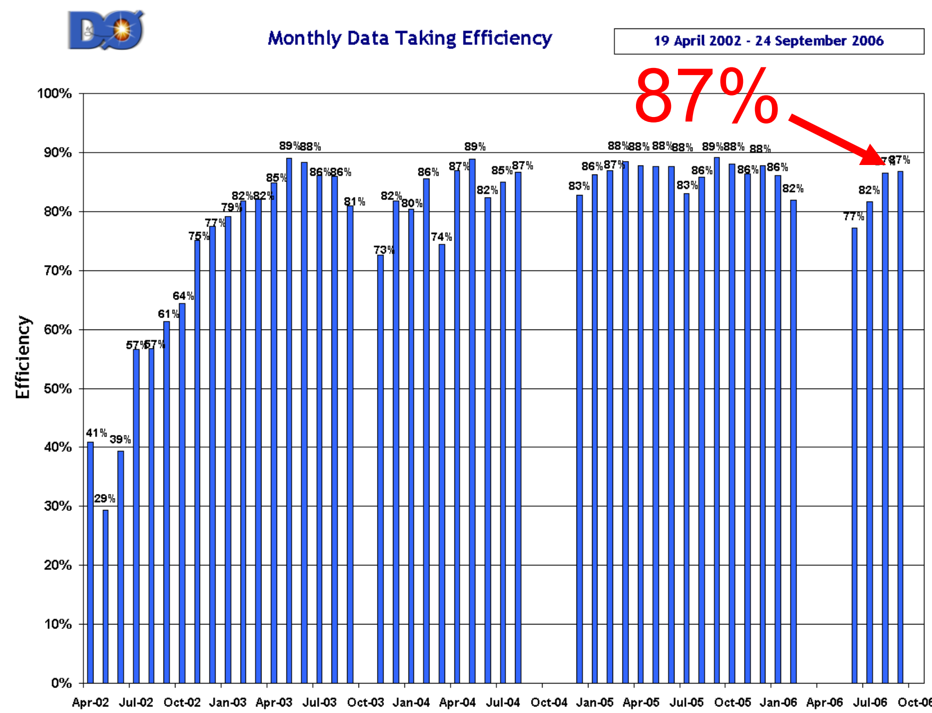
1.8T toroid followed by two similar tracking and trigger layers.

Good muon triggers produce high yield.

→ Large B samples.

DØ Detector





Data used in these analyses:

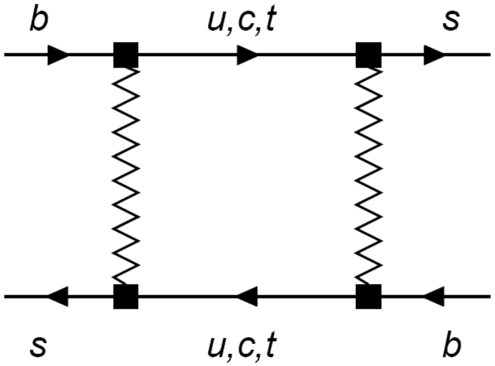
B_s Lifetime:	0.4 fb^{-1}
$\Delta\Gamma_s$: Br($B_s \to D_s^* D_s^*$):	1 fb^{-1}
$\Delta\Gamma_s$: $B_s \to J/\Psi\ \Phi$:	1 fb^{-1}

B_s Theory

Schrodinger Equation

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

B_s-$\overline{B}_s$ mixing



Two physical B_s eigenstates, B_H and B_L

B_H and B_L expected to have different masses and lifetimes.

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

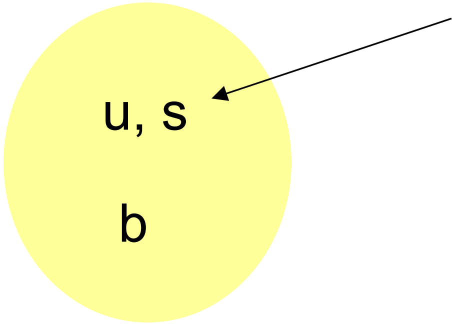
$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$$

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

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

B_s Lifetime

- **Spectator model** of heavy hadron decays predicts all hadrons with the same heavy flavor content have identical lifetimes.
- Observed charmed hadron lifetimes suggest non-spectator effects are not negligible in such decays.
- **Heavy Quark Expansion (HQE)** theory accounts for non-spectator effects in decays and predicts lifetime differences among different b hadrons.
- B-meson lifetime measurements tests the predictions of HQE theory.



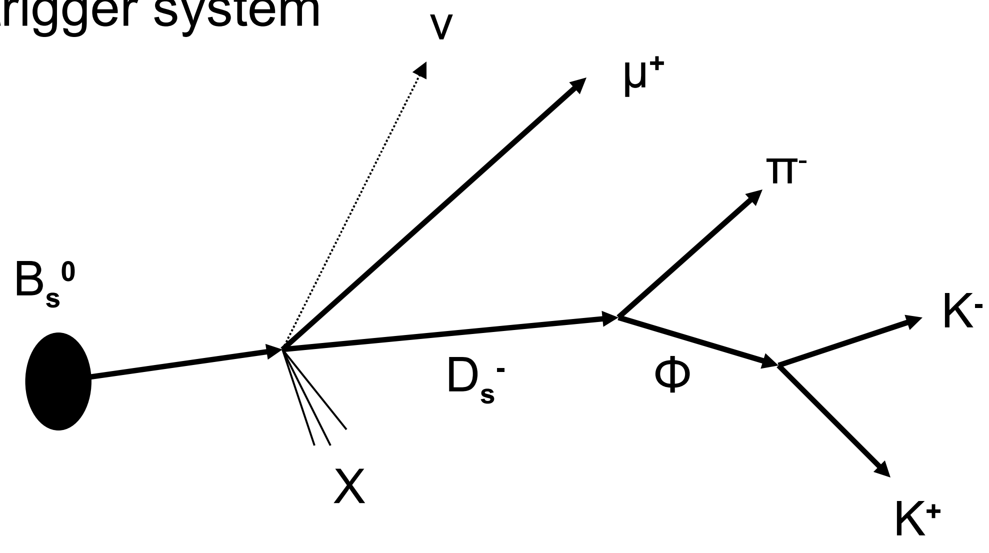
Spectator quark not negligible in b hadron lifetimes.

Hierarchy of B lifetimes

Test HQE prediction

Channel

- B_s identified through the semileptonic decay channel
  - $B_s \rightarrow D_s \mu \nu X$
  - $D_s \rightarrow \Phi \pi$
  - $\Phi \rightarrow K K$
- Events selected with inclusive single-muon triggers.
  - 3 level trigger system

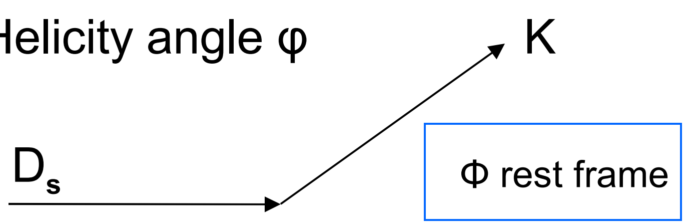


Selection

- Muon penetrates toroid
- All tracks within same jet
- χ^2 prob (D_s) > 0.1%
- χ^2 prob (B_s) > 0.01%
- Helicity(D_s) > 0.4
- Tracks with nSMT and nCFT ≥1
- No lifetime cuts!
- D_s decay vertex displaced from primary vertex in direction of P(D_s)

- $p_T(\mu) > 2.0$ GeV
- $p(\mu) > 3.0$ GeV
- $p_T(K) > 1.0$ GeV
- $p_T(\pi) > 0.7$ GeV
- $p_T(D_s) > 3.5$ GeV
- $p_T(\mu$ w.r.t $D_s) > 2.0$ GeV
- $1.008 < M(\Phi) < 1.032$ GeV
- $1.6 < M(D_s) < 2.3$ GeV
- $3.4 < M(B_s) < 5.0$ GeV

Helicity angle φ



Reconstruction

$D_s \to \Phi\,\pi$

- Tracks with $p_T > 1.0$ GeV assigned M(K)
- Oppositely charged pairs combined to form a Φ candidate.
- $1.008 < M(KK) < 1.032$ GeV.
- Φ Combined with a track with $p_T > 0.7$ GeV
  - Opposite charge from muon gives "right sign" combination.
  - Track assigned M(π)
- Three tracks (KKπ) used to form the D_s vertex.
- Additional track requirements:
  - At least one hit in SMT and CFT.
  - $p_T(D_s) > 3.5$ GeV

$B_s \to D_s\,\mu\,X$

- B_s decay vertex found by intersecting the μ track with the flight direction of the D_s candidate.
  - Required to be displaced from the primary vertex in the direction of the D_s momentum.
- $3.4 < \text{Mass}(B_s) < 5.0$ GeV/c^2
- B_s not fully reconstructed because neutrino is not detected.

Analysis

- B_s lifetime, τ, is related to the decay length, L_{xy}, in the transverse plane.

$$c\tau = m\, L_{xy} / p_T$$

τ = lifetime
p_T = transverse momentum of B_s
m = invariant B_s mass

  - Missing neutrino prevents a full reconstruction of the B_s.
  - Correction factor K introduced to estimate $p_T(B_s)$

$$K = p_T(D_s\,\mu) / p_T(B_s)$$

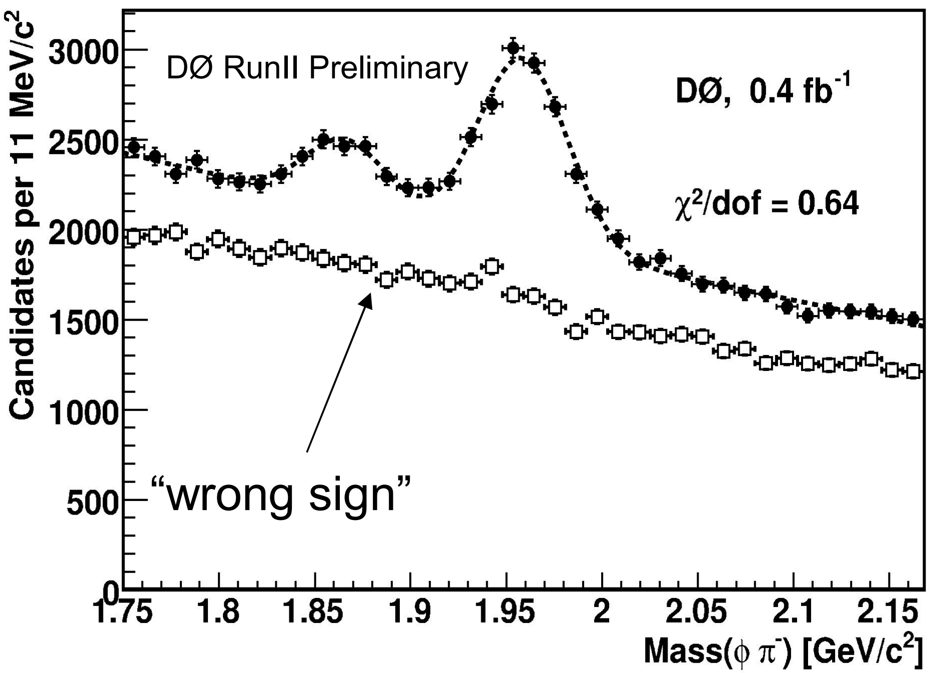
Determined with MC

  - Pseudo-proper decay length (PPDL), λ ,used to determine the B_s lifetime.

$$\lambda = L_{xy}\, m / p_T(D_s\,\mu) = c\tau / K$$

Signal

- Signal: Gaussian fit to "right-sign" $D_s\mu$ candidates.
- Background: second-order polynomial fit.
- $D \rightarrow \Phi\pi$(Cabbibo suppressed): Gaussian fit.



Reconstructed D_s candidates

400 pb^{-1}

5176 ± 242 (stat) ± 314 (syst)

$M(D_s)$ = 1958.8 ± 0.9 MeV

Background

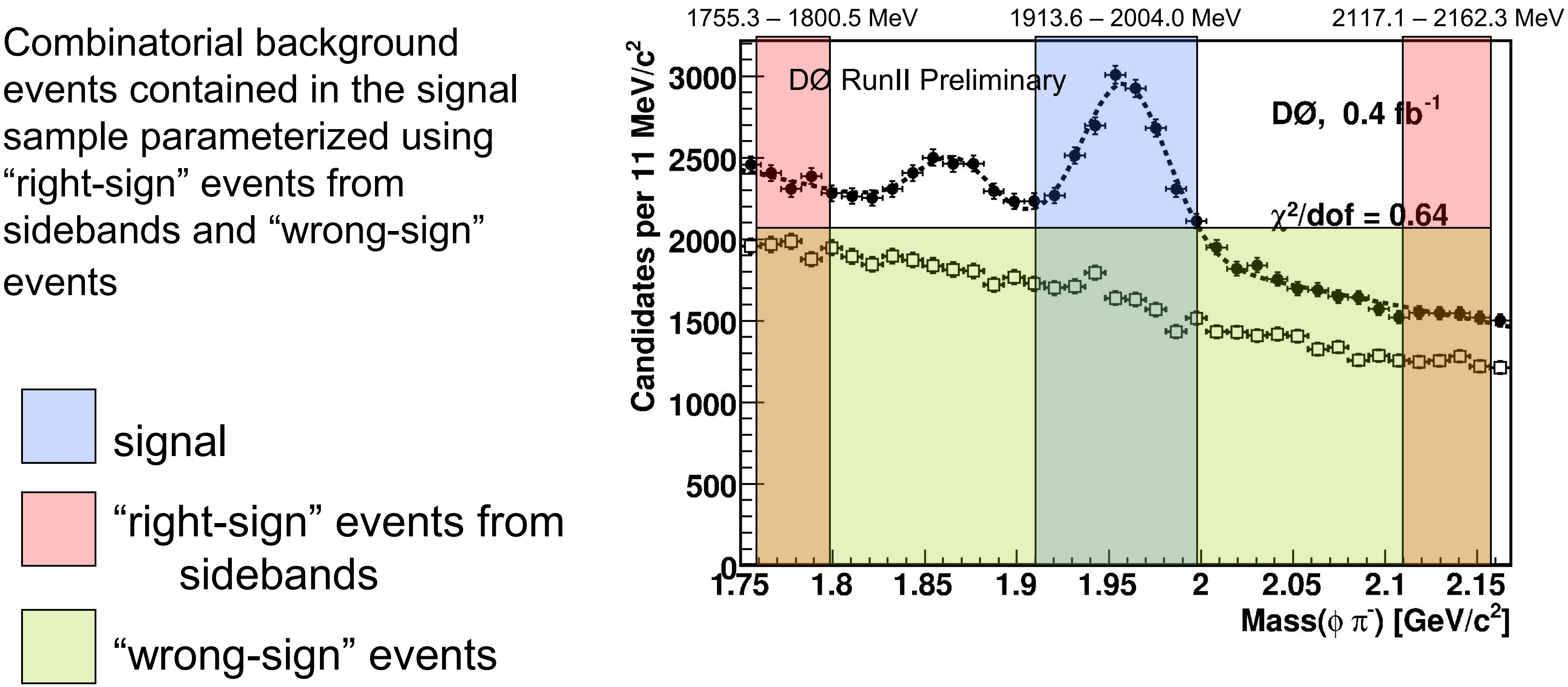
- "Prompt"
  - μ produced at primary vertex + reconstructed D_s
- "Physics Background"
  - μ + D_s where neither come from semileptonic decay of B_s
  - Included in signal sample
  - Prompt D_s from cc production + μ
  - Short lifetimes
  - Can bias lifetime measurement
- "Non-B_s Background"
  - $B \to \mu D_s$
  - Long lifetimes
  - Smaller effects
  - Softer $p_T(\mu)$ from decay of secondary c-hadron
  - Reduced by kinematic cuts

$B^0 \to D_s^{*-} D^{*+} X$
$B^- \to D_s^{*-} D^{*0} X$
$B_s \to D_s^{*-} D^* X$

- Background contribution of each process evaluated with MC.

Background

- Combinatorial background events contained in the signal sample parameterized using "right-sign" events from sidebands and "wrong-sign" events



Fit

- PPDL distribution from signal region fitted with an unbinned maximum log-likelihood method.
- Both B_s lifetime and background shape determined in a simultaneous fit to the signal and background samples.

$$\mathcal{L} = C_{sig} \prod_{i}^{N_S} [f_{sig}\mathcal{F}^i_{sig} + (1 - f_{sig})\mathcal{F}^i_{bck}] \prod_{j}^{N_B} \mathcal{F}^j_{bck},$$

N_S – Number of events in signal sample

N_B – Number of events in background sample

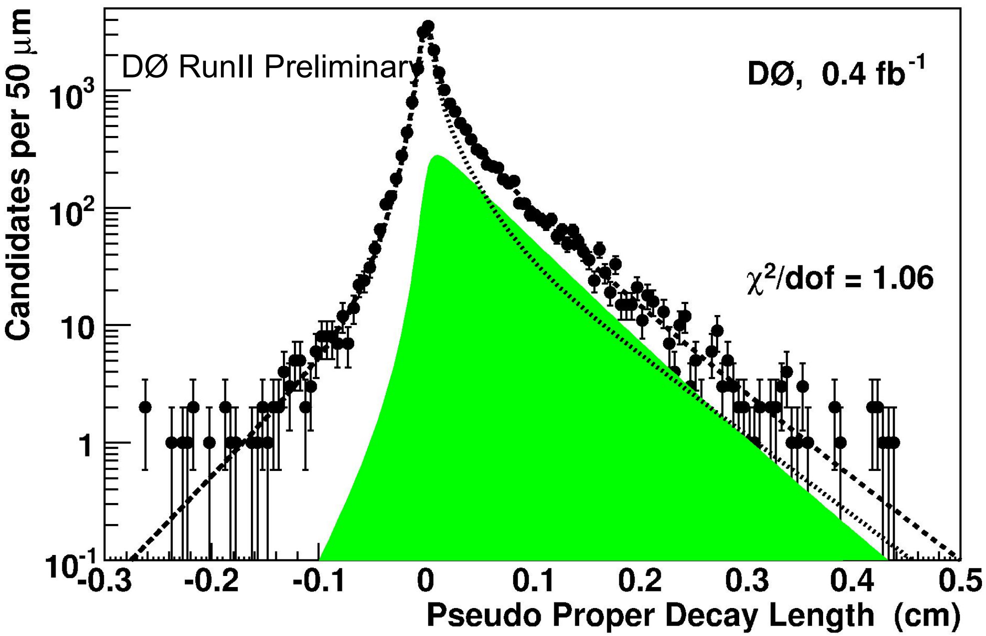
f_{sig} – ratio of D_s signal events from mass distribution to total number of events in the signal sample

F_{sig} – signal probability distribution function (normalized exponential decay, K factor, and a gaussian resolution function.

F_{bkg} – combinatorial background sample

Results

- $\tau(B_s) = 1.398 \pm 0.044\ (\text{stat})\ ^{+0.028}_{-0.025}\ (\text{syst})$ ps
- Most precise result to date!
- WA_{PDG}: $\tau(B_s) = 1.461 \pm 0.057$ ps
- $\tau(B^0) = 1.536 \pm 0.014$ (stat) ps
- B_s lifetime is different from the B^0 lifetime by more than 1%, consistent with HQE.



Source	Syst. Uncertainty (ps)
Detector alignment	±0.007
Combinatorial background	±0.014
Selection criteria	+0.01 -0.0001
K factor determination	+0.012 -0.007
Decay length resolution	±0.012
non-B_s background	+0.010 -0.014
ccbar background	+0.008 -0.003
Total	**+0.028** **-0.025**

Comparison to other results.

Experiment	dataset	$\tau(B_s^0)$ (ps)
World Average(PDG) [11]		1.461 ± 0.057
ALEPH	91-95	$1.54^{+0.14}_{-0.13} \pm 0.04$
CDF	92-96	$1.36 \pm 0.09^{+0.06}_{-0.05}$
DELPHI	91-95	$1.42^{+0.14}_{-0.13} \pm 0.03$
OPAL	90-95	$1.50^{+0.16}_{-0.15} \pm 0.04$
Average of $D_s l$ measurements [16]		1.442 ± 0.066
CDF [17]	02-04	$1.381 \pm 0.055^{+0.052}_{-0.046}$
This Measurement	02-04	$1.398 \pm 0.044^{+0.028}_{-0.025}$

[hep-ex/0604046]

$\Delta\Gamma_s$: Br($B_s \to D_s^* D_s^*$)

$\Delta\Gamma_s = \Gamma_L - \Gamma_H$

$|B_L\rangle = |B_s^{EVEN}\rangle$
$|B_H\rangle = |B_s^{ODD}\rangle$

$\Delta\Gamma_{CP} = \Gamma(B_s^{EVEN}) - \Gamma(B_s^{ODD})$

- How to measure $\Delta\Gamma_s$?
  - Directly from $B_s \to J/\Psi\ \Phi$ decays
    - Disentangle CP even and odd final states.
  - Estimate from Br($B_s \to D_s^* D_s^*$)
    - CP even dominated final state
    - Gives largest contribution in the lifetime difference.

Theory suggest:

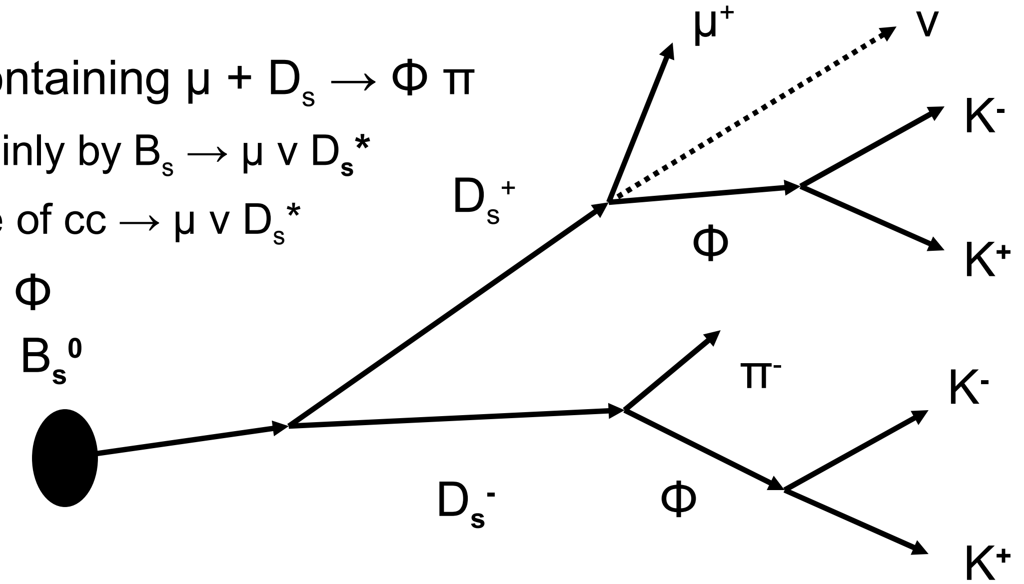
$$2\,Br(B_s \to D_s^* D_s^*) \approx \Delta\Gamma_{CP} / \Gamma\ (1 + O(\Delta\Gamma/\Gamma))$$

- Relate measurement to CPV phase, Φ_s
  - $\Delta\Gamma_{CP} = \Delta\Gamma / \cos\Phi_s$
  - Φ_s is related to CP violation in B_s mixing and is expected to be small in the SM.

Channel

- B_s identified through decay to two D_s^*
  - $B_s^0 \to D_s^* D_s^*$
  - $D_s^* \to \mu^+ \nu \Phi$, $\Phi \to K^+ K^-$ (semileptonic)
  - $D_s^* \to \Phi \pi^-$, $\Phi \to K^+ K^-$ (hadronic)

- Define 2 Samples
  - (μD_s): events containing $\mu + D_s \to \Phi \pi$
    - Produced mainly by $B_s \to \mu \nu D_s^*$
    - Small sample of $cc \to \mu \nu D_s^*$
  - ($\mu\Phi D_s$): (μD_s) + Φ



Analysis

- Estimate the following;
  - $N(\mu D_s)$ – number of signal events in (μD_s) sample
  - $N(\mu\Phi D_s)$ – number of signal events in $(\mu\Phi D_s)$ sample
  - $f(B_s \to \mu\nu D_s^*)$ – fraction of $B_s \to \mu\nu D_s^*$ decays in (μD_s) sample
  - $N_{bkg}(\mu\Phi D_s)$ – Number of background events in $(\mu\Phi D_s)$ sample
    - $f(B_s \to \mu\nu D_s^*)$ and $N_{bkg}(\mu\Phi D_s)$ determine by subtracting contributions from all other sources from each sample

- Measure R (detector uncertainties cancel) and extract the branching ratio.
  - $R \propto N(\mu\Phi D_s) - N_{bkg}(\mu\Phi D_s) / N(\mu D_s)\, f(B_s \to \mu\nu D_s)$
  - $R = Br(B_s \to D_s^* D_s^*)\, Br(D_s \to \mu\nu\Phi) / Br(B_s \to \mu\nu D_s^*)$

- Compute $Br(B_s \to D_s^* D_s^*)$ using;
  - Measured value of R
  - PDG value for $Br(D_s \to \mu\nu\Phi)$
  - PDG value for $Br(B_s \to \mu\nu D_s^*)$
  - BaBar measurement of $Br(D_s \to \Phi\pi)$ – combined average with PDG

Selection

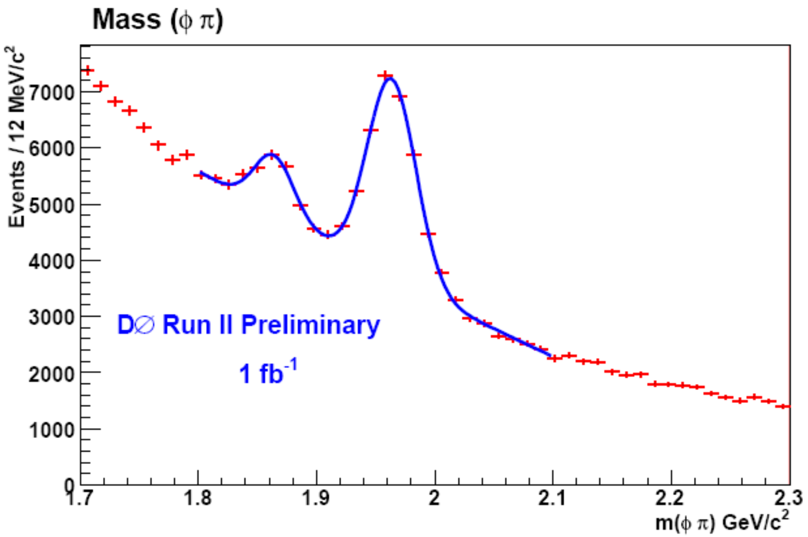
- Number of muon hits ≥ 2
- All tracks:
  - nSMT hits ≥ 2
  - nCFT hits ≥ 2
- $P_T(\mu) > 2$ GeV
- $P(\mu) > 3$ GeV
- $P_T(\pi) > 1.0$ GeV
  - Opposite charge from μ
- $P_T(K) > 0.8$ GeV
  - Opposite charge combinations
- $\Phi(D_s \to \Phi\pi)$: $1.01 < m(KK) < 1.03$ GeV
- $\Phi(D_s \to \Phi\mu)$: $0.998 < m(KK) < 1.07$ GeV

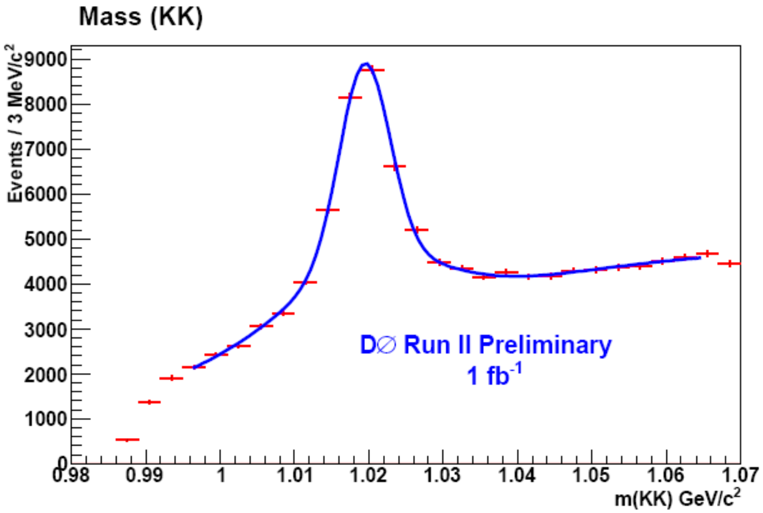
- $D_s \to \Phi\pi$
  - $1.7 < m(\Phi\pi) < 2.3$ GeV
  - χ^2 (vertex) < 16
  - $|\cos(\theta)| > 0.35$, Helicity between D_s and K
- $D_s \to \Phi\mu\nu$
  - $1.2 < m(\Phi\mu) < 1.85$ GeV
  - χ^2 (vertex) < 16
- $B_s \to \mu D_s$
  - $m(\mu D_s) < 5.2$ GeV
  - χ^2 (B vertex) < 16
  - $L(\mu D_s) > 150$ μm
- $D_s \to \mu\Phi D_s$
  - $4.3 < m(\mu\Phi D_s) < 5.2$ GeV
  - χ^2 (vertex) < 16
  - $L(\mu\Phi D_s) > 150$ μm

N(μDs) Sample

- Number of (μD_s) events estimated from a binned fit to M(Φπ) distribution.
- Gaussian fit to both D and D_s decays
- Second-order polynomial fit to background

$N(\mu D_s) = 15225 \pm 310$

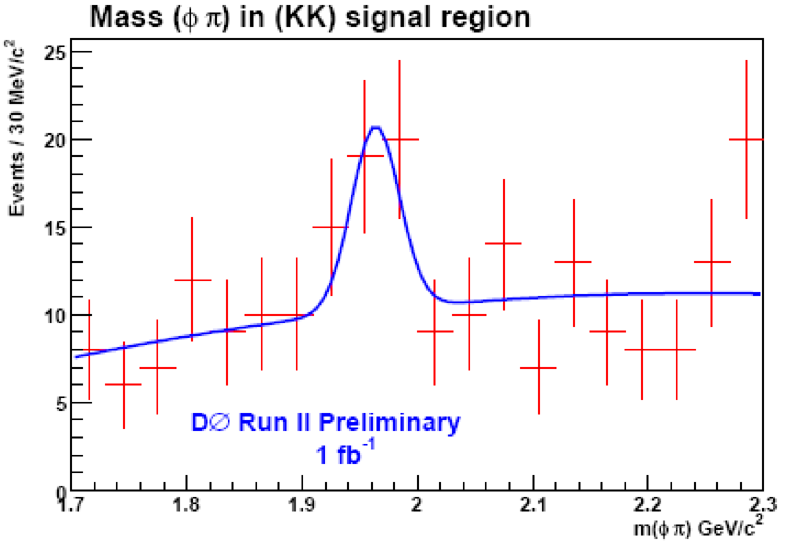


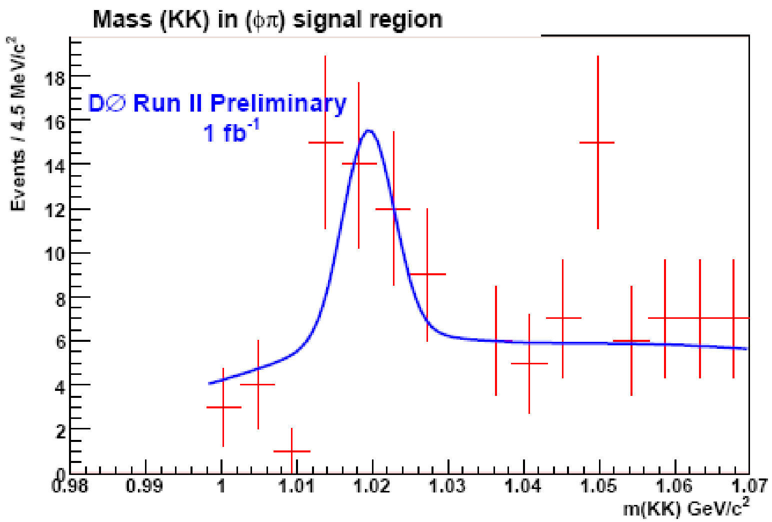


N(μΦDs) Sample

- Number of ($\mu\Phi D_s$) events estimated from an unbinned Log-Likelihood fit.
  - Used all events in range
    - $1.7 < M(D) < 2.3$ GeV
    - $0.998 < M(\Phi) < 1.07$ GeV
  - Single Gaussian used to describe the D_s signal
  - Double Gaussian used to describe the Φ peak.

$N(\mu\Phi D_s) = 19.34 \pm 7.85$





Sample Composition

Process	Br(%)
$Br(B_s \to \mu\nu D_s)$	2.10
$Br(B_s \to \mu\nu D_s^*)$	5.60
$Br(B_s \to \mu\nu D_{s0}^*)$	0.20
$Br(B_s \to \mu\nu D'_{s1})$	0.37
$Br(B_s \to \tau\nu D_s^*)\ Br(\tau \to \mu\nu)$	0.51

Process	Br(%)
$B^0 \to D_s D^* X$	10.5 ± 2.6
$B^\pm \to D_s D^* X$	10.5 ± 2.6
$B_s \to D_s^* D_s^*$	$12\,_{-7}^{+11}$
$B_s \to D_s D X$	15.4 ± 15.4

Fraction of events in (μD_s) sample coming from $B_s \to \mu\nu D_s X$

$$f(B_s \to \mu\nu D_s^*) = 0.79 \pm 0.05$$

Background Composition

Processes Contributing to N_{bkg} ($\mu\Phi D_s$)	Number of Events
$B_s \rightarrow D_s^* D_s^*$	
$B \rightarrow D_s^* D_s^* KX$	0.44 ± 0.30
$B_s \rightarrow D_s^* D_s^* X$	~0
$B_s \rightarrow \mu\nu D_s^* \Phi$	1.27 ± 1.14
$cc \rightarrow \mu\Phi D_s^*$	~0
$B_s \rightarrow \mu\nu D_s^*$ and Φ from fragmentation.	~0

N_{bkg} ($\mu\Phi D_s$) = 1.7 ± 1.2

Results

$N(\mu D_s)$	15225 ± 310
$N(\mu \Phi D_s)$	19.34 ± 7.85
$f(B_s \to \mu\nu D_s)$	0.79 ± 0.05
$N_{bkg}(\mu \Phi D_s)$	1.7 ± 1.2
$Br(D_s \to \Phi\pi)_{BaBar}$	4.81 ± 0.52 ± 0.38

Source	Uncertainty in $Br(B_s \to D_s^* D_s^*)$
$Br(D_s \to \Phi\pi) = 0.0440 \pm 0.0520$	+0.020 -0.014
$Br(B_s \to \mu\nu D_s^*)\ Br(D_s \to \Phi\pi)$	±0.012
$Br(D_s \to \Phi\mu\nu) / Br(D_s \to \Phi\pi)$	±0.005
$f(B_s \to \mu\nu D_s^*) = 0.79 \pm 0.05$	±0.005
Background contribution in $N(\mu\Phi D_s)$	±0.007
Ratio of efficiencies	±0.010
Reweighting of MC	±0.011

$Br(B_s \to D_s^* D_s^*) = 0.071 \pm 0.032\ (stat)\ _{-0.025}^{+0.029}\ (syst)$

$\Delta\Gamma_{CP} / \Gamma = 0.142 \pm 0.064\ (stat)\ _{-0.050}^{+0.058}\ (syst)$

This estimate is in good agreement with the SM predictions

$\Delta\Gamma_{CP} / \Gamma_{SM} = 0.12 \pm 0.06$

[DØ Conference Note 5068]

$\Delta\Gamma_s$: $B_s \to J/\Psi\ \Phi$

- To a good approximation, mass eigenstates in B_s system are expected to be CP eigenstates.
- New phenomena may introduce a non-vanishing mixing phase $\delta\Phi_s$, leading to a reduction in the observed $\Delta\Gamma$ compared to SM predictions $\Delta\Gamma_{SM}$:
  - $\Delta\Gamma = \Delta\Gamma_{SM} * |\cos(\delta\Phi_s)|$
- $B_s \to J/\Psi\ \Phi$ gives rise to a mixture of CP-even and CP-odd final states.
- Possible to separate the two CP components of the decay and measure the lifetime differences.
  - Simultaneous fit to the mass, proper decay length, and three angles of the decay products J/Ψ and Φ.

Selection

- $B_s \to J/\Psi\ \Phi$
  - $J/\Psi \to \mu\mu$
  - $\Phi \to KK$
- 2 Reconstructed μ's
- Number muon hits ≥ 1
- $P_T(\mu) > 1.5$ GeV
- $P_T(K) > 0.7$ GeV
- $P_T(\Phi) > 1.5$ GeV
- $P_T(B_s) > 6.0$ GeV

$2.9 < M(J/\Psi) < 3.3$ GeV

$1.01 < M(\Phi) < 1.03$ GeV

$5.0 < M(Bs) < 5.8$ GeV

J/Ψ and Φ have common vertex

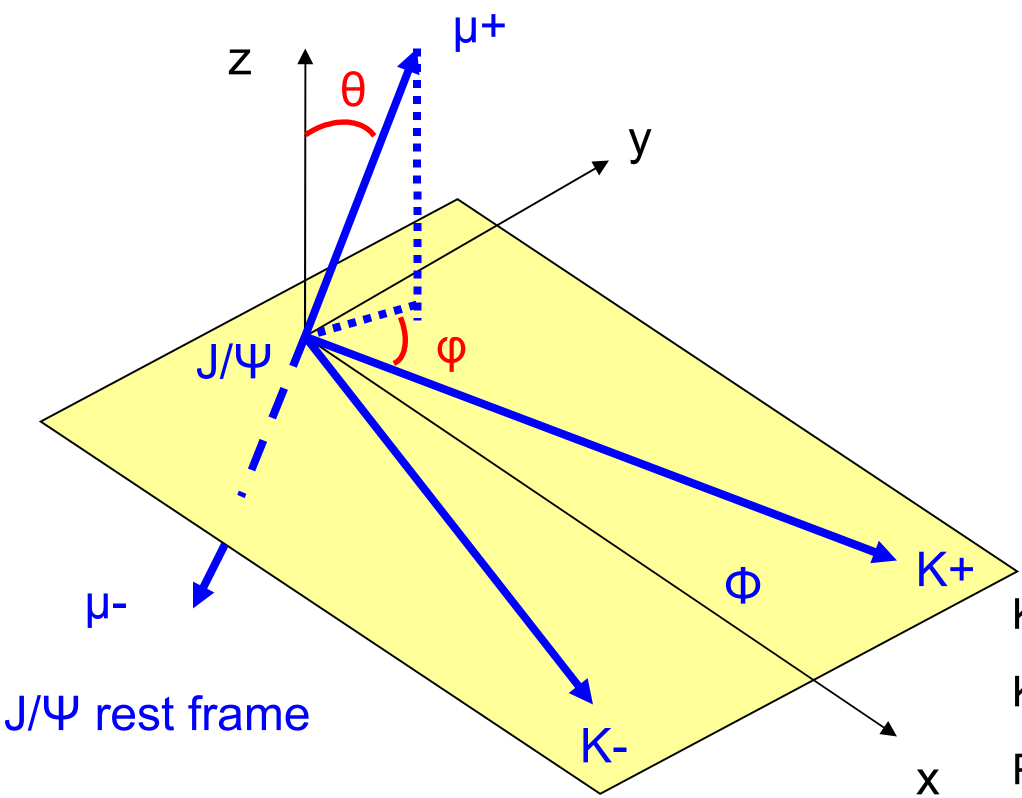
$\sigma(ct) < 60$ μm

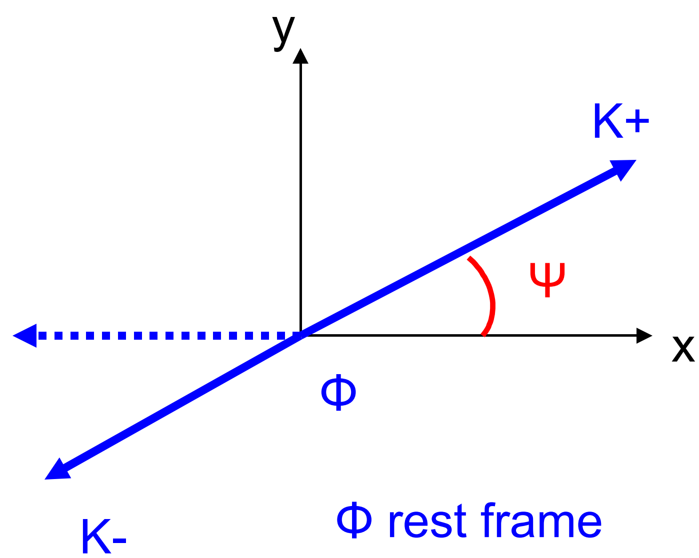
$c\tau = L_{xy}\, M_B / p_T$

23343 candidates

3 Angle Analysis

- The CP content $B_{s\rightarrow} J/\Psi\ \Phi$ can be analyzed by studying the 3 angular distributions (φ, θ, Ψ) of the decay products.





KK defines xy plane

K^+ defines +y direction

Polar and azimuthal angles of μ^+, θ and φ

Helicity angle Ψ

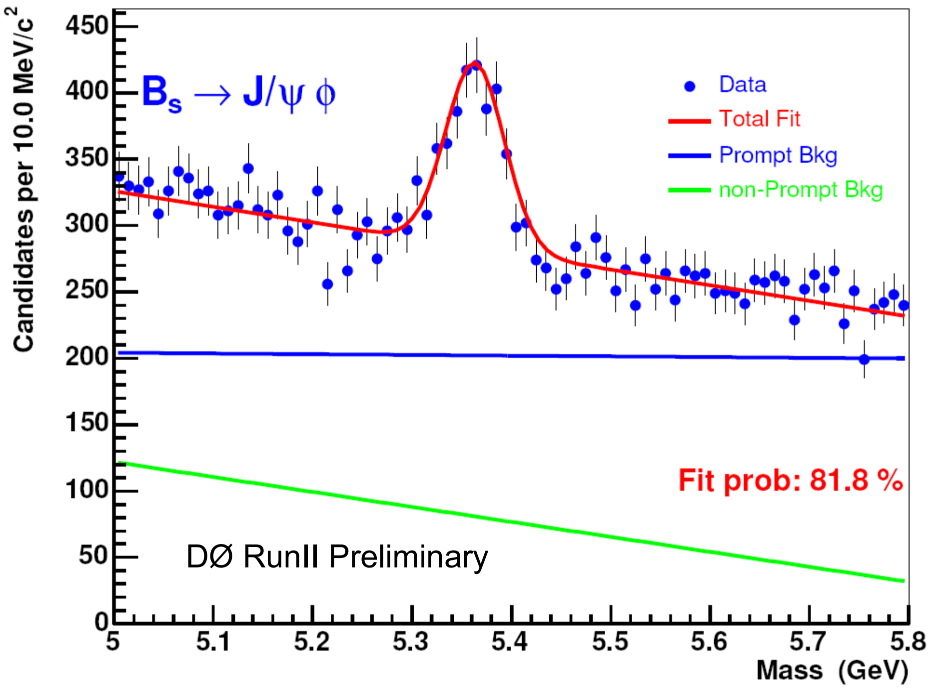
Background

- Background is divided into two categories:
  - "Prompt" – directly produced J/Ψ mesons formed together with random tracks.
    - Fitted with a gaussian function
  - "Non-prompt" – J/Ψ product of B decay and Φ tracks come from same B hadron
    - Fitted with two exponentials: negative and positive cτ regions.

Fit

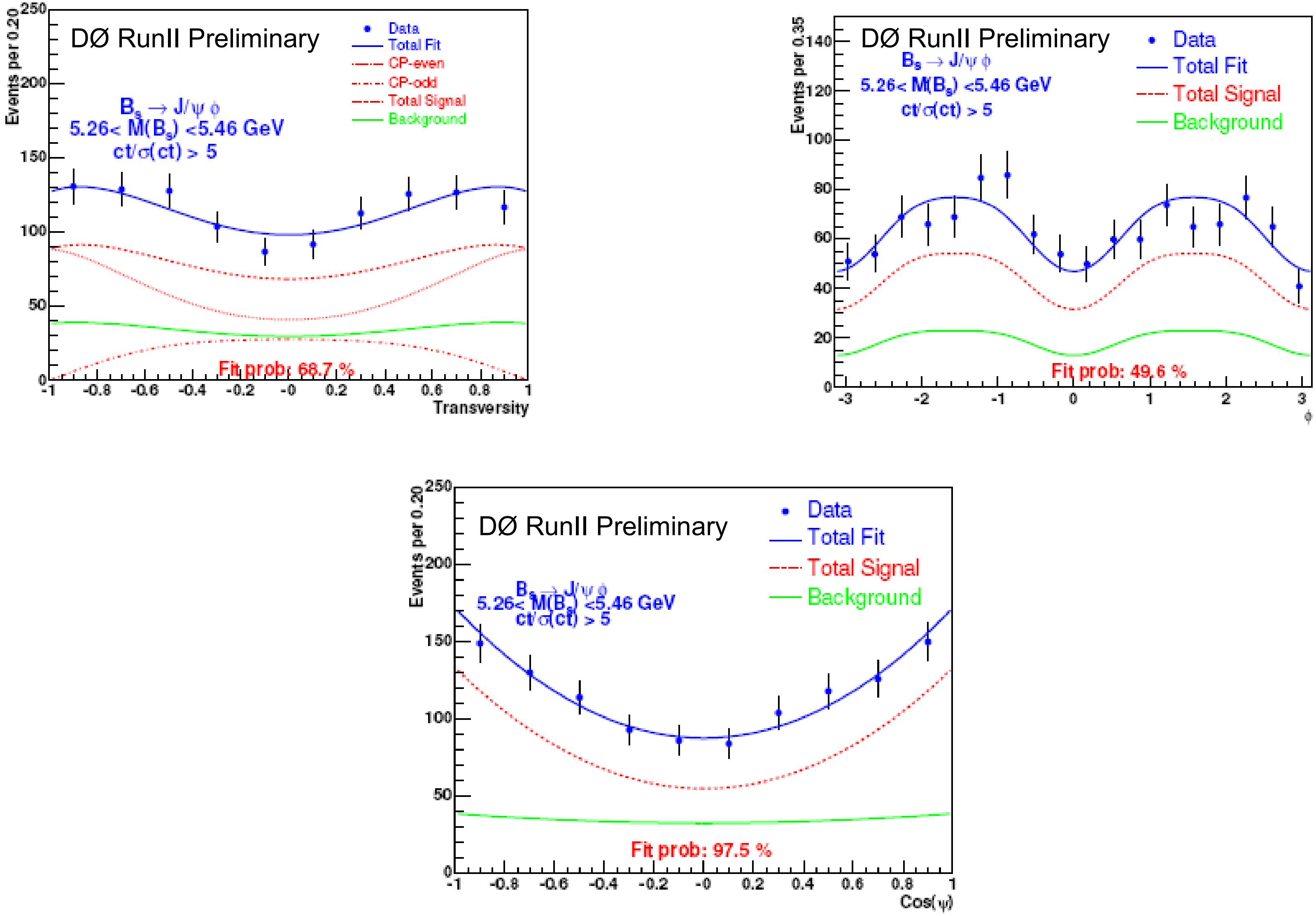
- Simultaneous unbinned maximum likelihood fit to the proper decay length, three angles, and the B_s mass.

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

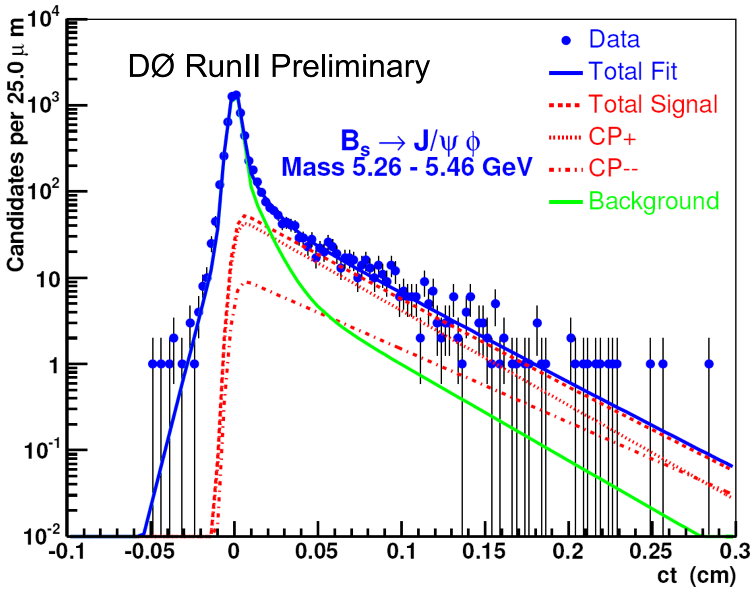


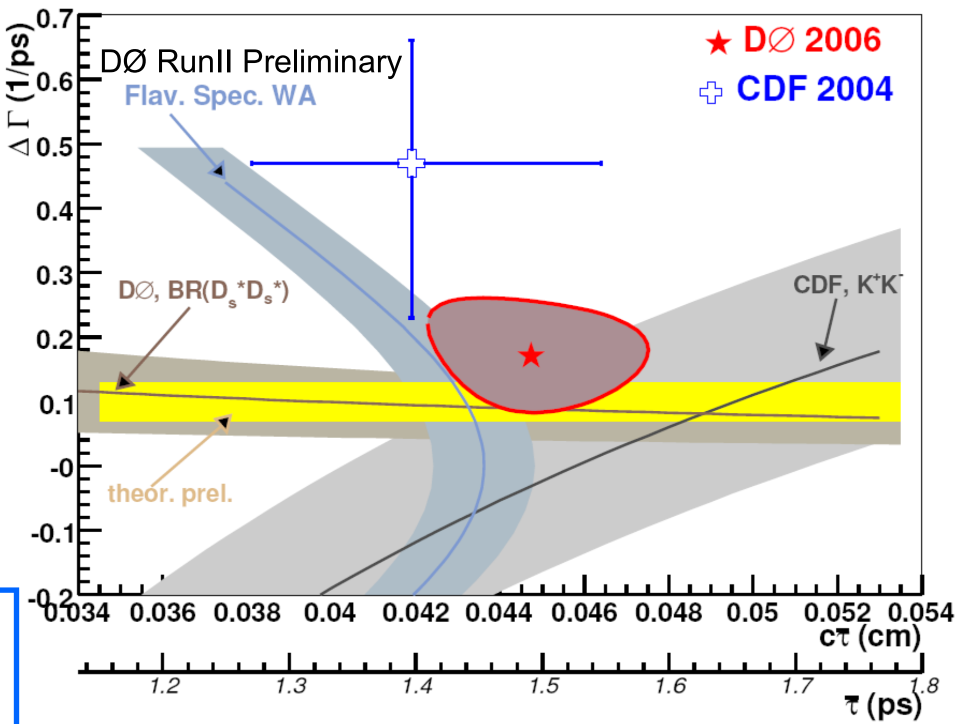
- N – total number of events
- f_{sig} – signal fraction
- F_{sig} – function of the signal mass, proper decay length, and the decay angles (φ, θ, Ψ) .
- F_{bkg} – product of the background mass, proper decay length, and angular density functions.

Angular Fit Results



Results





No CP violation hypothesis ($\delta\Phi = 0$)

$\overline{\tau}(B_s) = 1.52 \pm 0.08 \text{ (stat)}\ ^{+0.01}_{-0.03} \text{ (syst) ps}$

$\Delta\Gamma = 0.12 \pm 0.08 \pm 0.03$ ps-1

CPV ($\delta\Phi$ allowed to vary)

$\overline{\tau}(B_s) = 1.49 \pm 0.08 \text{ (stat)}\ ^{+0.01}_{-0.03} \text{ (syst) ps}$

$\Delta\Gamma = 0.17 \pm 0.09 \pm 0.03 \text{ ps}^{-1}$

$\delta\Phi = -0.79 \pm 0.56 \pm 0.01$, $\delta\Phi_{SM} = -0.03$

[DØ Conference Note 5144]

Summary

- DØ continues to produce interesting and competitive results in B physics
- Most precise results to date on B_s lifetime!
  - $\tau(B_s) = 1.398 \pm 0.044\,(\text{stat})\,^{+0.028}_{-0.025}\,(\text{syst})$ ps
  - Stringent test of HQE theory
- Tests of Standard Model
  - $Br(B_s \rightarrow D_s^* D_s^*) = 0.071 \pm 0.032\,(\text{stat})\,^{+0.029}_{-0.025}\,(\text{syst})$

    $\Delta\Gamma_{CP} / \Gamma = 0.142 \pm 0.064\,(\text{stat})\,^{+0.058}_{-0.050}\,(\text{syst})$
  - $B_s \rightarrow J/\Psi\,\Phi$

    $\tau(B_s) = 1.49 \pm 0.08\,(\text{stat})\,^{+0.01}_{-0.03}\,(\text{syst})$ ps

    $\Delta\Gamma = 0.17 \pm 0.09 \pm 0.03$ ps^{-1}

Backup Slides

$\Delta\Gamma_s$: Fit

- The time evolution of the three-angle distribution of the products of the decay of untagged B_s mesons, expressed in terms of the linear polarization amplitudes $|A_x(t)|$

$$\frac{d^3\Gamma(t)}{d\cos\theta\ d\varphi\ d\cos\psi} \propto\ 2|A_0(0)|^2\ \mathcal{T}_+\ \cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$

$$+\sin^2\psi\{|A_\parallel(0)|^2\ \mathcal{T}_+\ (1-\sin^2\theta\sin^2\varphi)+|A_\perp(0)|^2\ \mathcal{T}_-\ \sin^2\theta\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\ \mathcal{T}_+\ \sin^2\theta\sin 2\varphi$$

$$+\left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\varphi\right.$$

$$\left.-|A_\parallel(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\varphi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin(\delta\phi)\ .$$

where, $\mathcal{T}_+ = \frac{1}{2}\left((1+cos\delta\phi)e^{-\Gamma_L t}+(1-cos\delta\phi)e^{-\Gamma_H t}\right)$ and $\mathcal{T}_- = \frac{1}{2}\left((1-cos\delta\phi)e^{-\Gamma_L t}+(1+cos\delta\phi)e^{-\Gamma_H t}\right)$.