Selected B Results

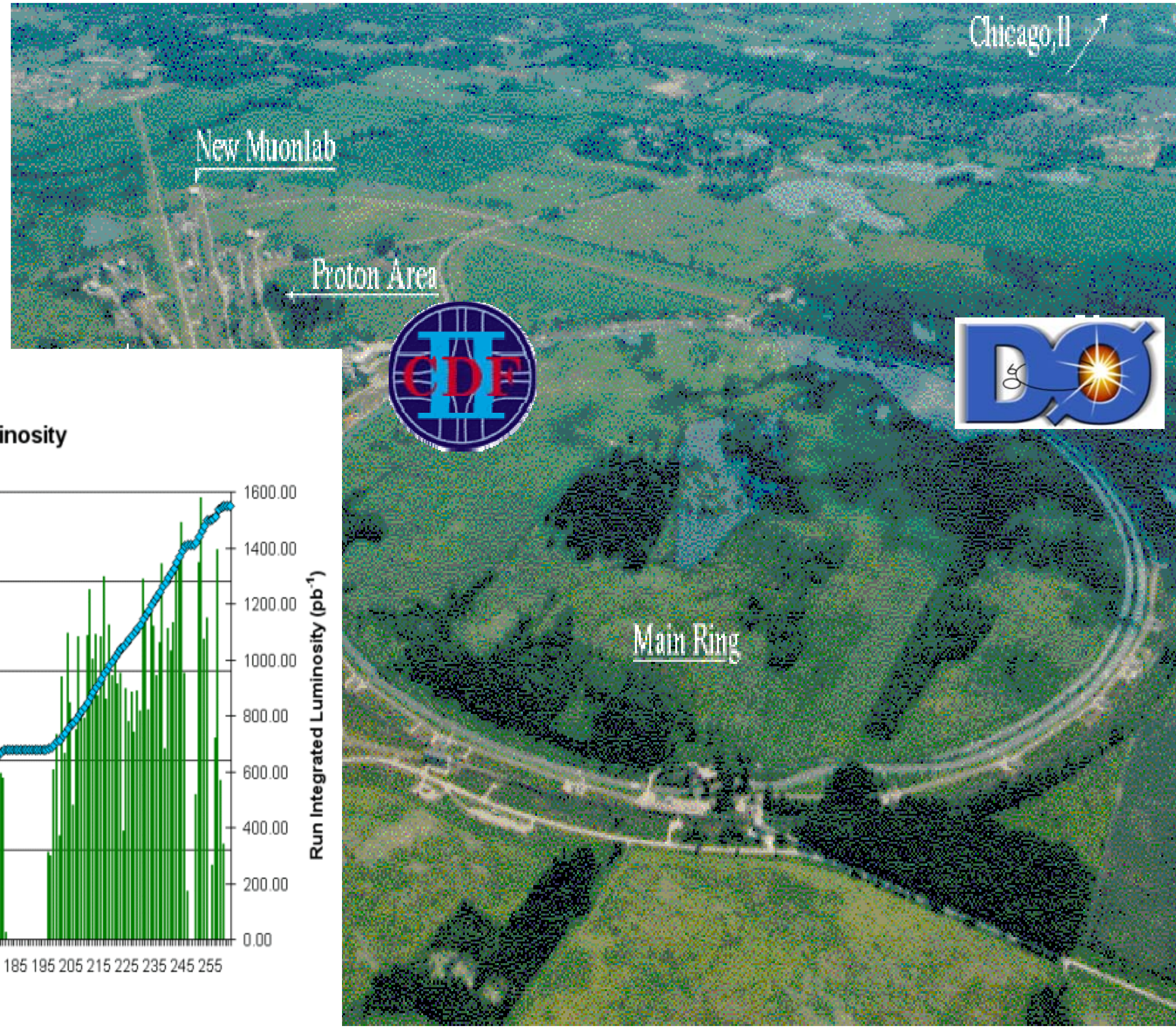
From the other B factory

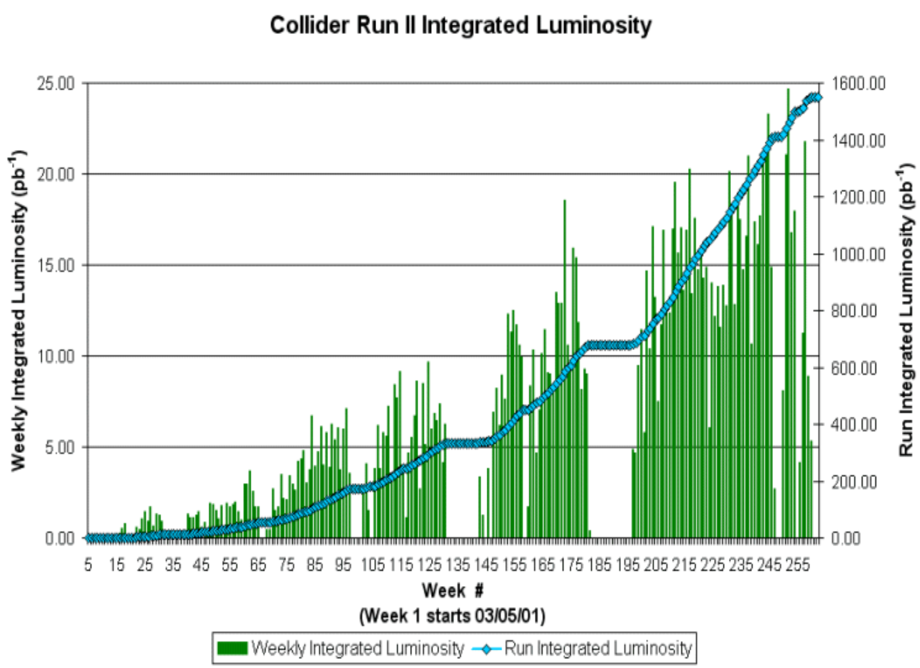
- Collider and Detectors
- B hadron spectroscopies
  - Λ_b lifetime
  - $Br\left(B_s^0 \to D_s^{(*)} D_s^{(*)}\right)$
  - B^{**}, B_{s2}^{*}
  - B_c mass
- FCNC rare decays
  - $B_d^0, B_s^0 \to \mu^+\mu^-$
  - $B_s^0 \to \mu^+\mu^-\phi$
  - $D^+ \to \mu^+\mu^-\pi^+$
- Bs mixing and lifetimes
  - lifetime difference $\Delta\Gamma_s$
  - oscillation frequency Δm_s

On behalf of CDF and DØ Collaboration

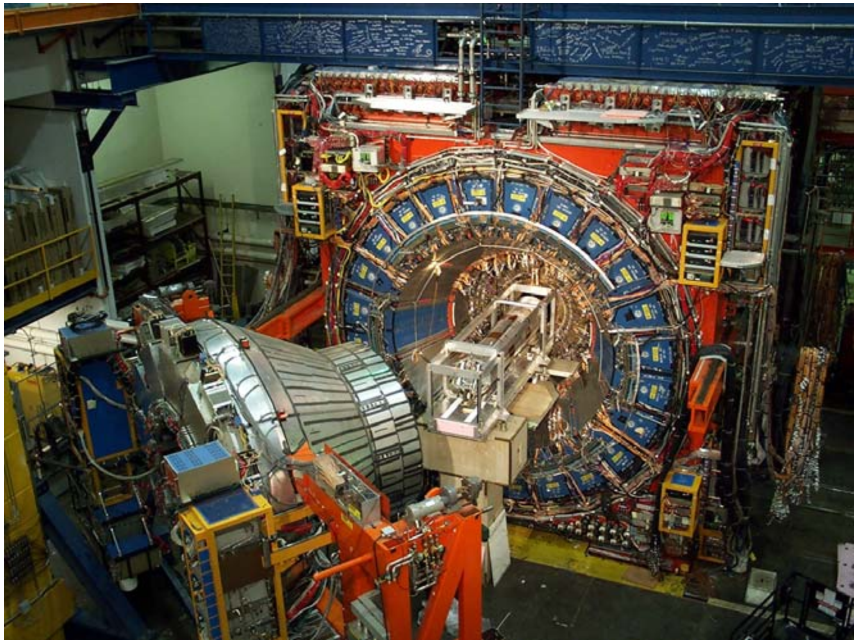
Tevatron Collider

- integrated luminosity delivered:
  ~1.6 fb^{-1}
  per experiment
- record instantaneous luminosity:
  $1.7 \times 10^{32}\ cm^{-2}\ s^{-1}$





The Detectors



CDF:

Recorded 1.4 fb^{-1}

B physics capability:
large tracking volume,
vertex trigger,
large tracker,
particle ID,
large trigger bandwidth ...

DØ:

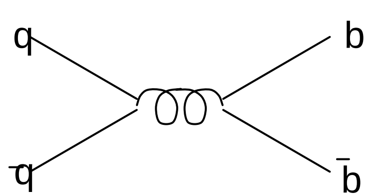
recorded 1.2 fb^{-1}

B physics capability:
a magnetic compact tracker,
large muon coverage, ...

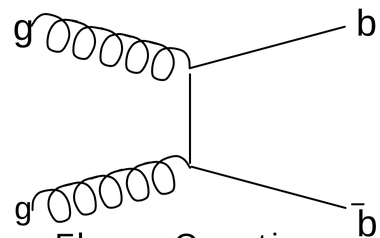
B Production @ Tevatron

Good: Larger b cross section
~ 100 μb → 10kHz real b's

Bad: even larger cross section from QCD backgrounds ~ 50 mb !



Flavor Creation
(annihilation)

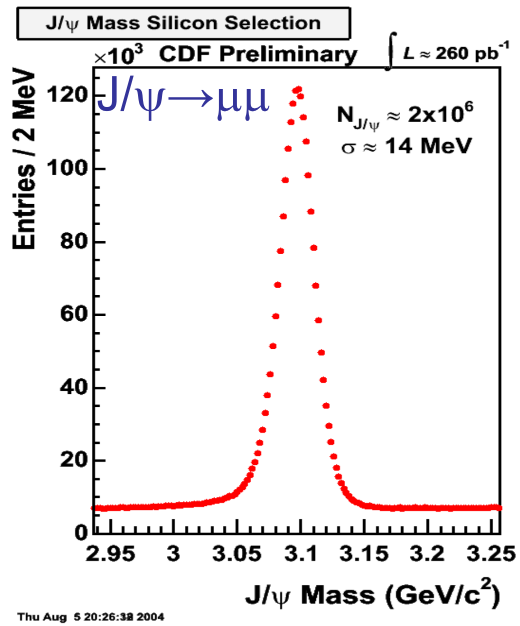


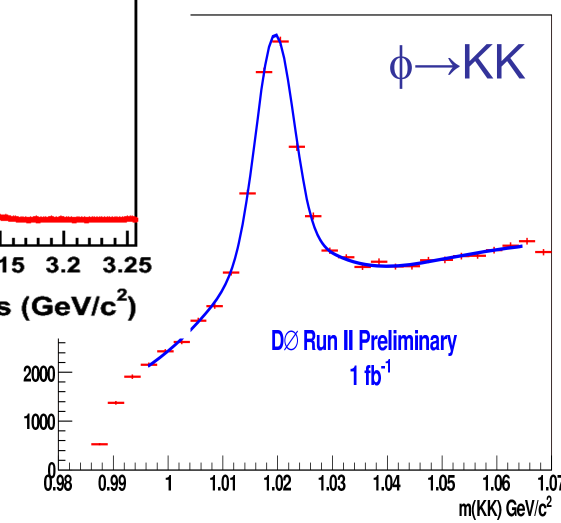
Flavor Creation
(gluon fusion)

+…

Keys:

- **Trigger to select b candidates**
  - **CDF: μ, secondary vertex;**
  - **DØ: μ only**
- **Large bandwidth to record them**
  - **CDF: ~ 100 Hz to tape**
  - **DØ: 50 Hz**



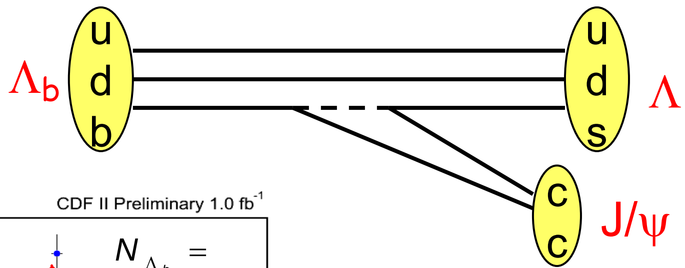


All kind of B hadrons are produced: B_d, B_s, B_c, B^{**}, Λ_b, Ξ_b, …

- **B^+, B: ~80%**
- **B_s, b-baryon: ~10%**
- **B_c: ~0.05%**

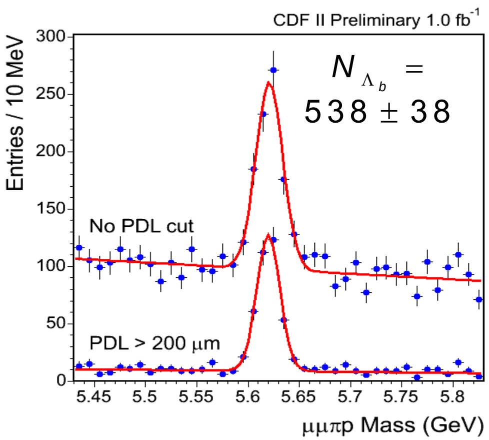
Λ_b Lifetime

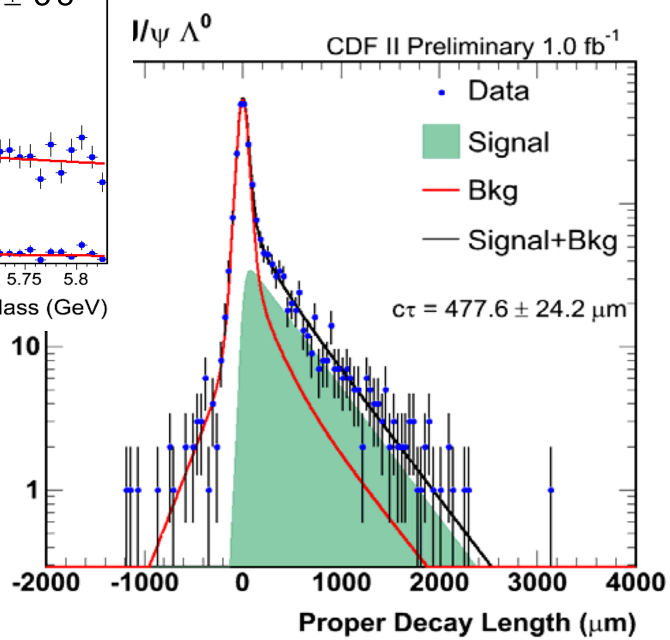
A (udb) baryon, the lightest with a b-quark

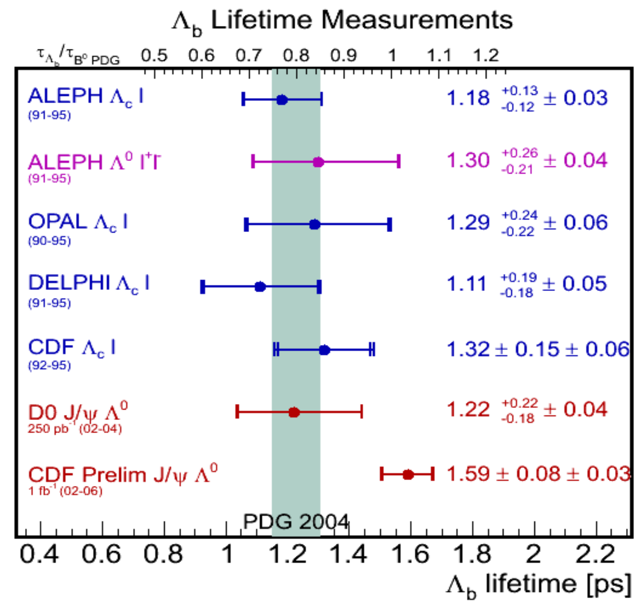


Full $\Lambda_b \to J/\psi\ \Lambda$ reconstruction with $J/\psi \to \mu\mu$ and $\Lambda \to p\pi$

$B_d \to J/\psi(\mu\mu)\ K_s(\pi\pi)$ for cross checks







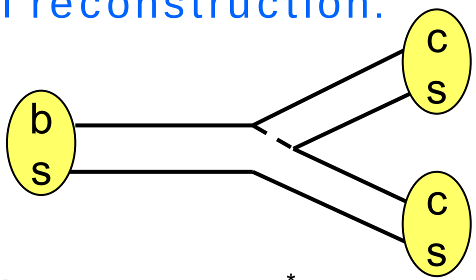
World's Best !

$$\tau = 1.593^{+0.083}_{-0.078}(stat) \pm 0.033(syst)\ \text{ps}$$

The new measurement appears to be "interestingly" above the previous world average. Time will tell…

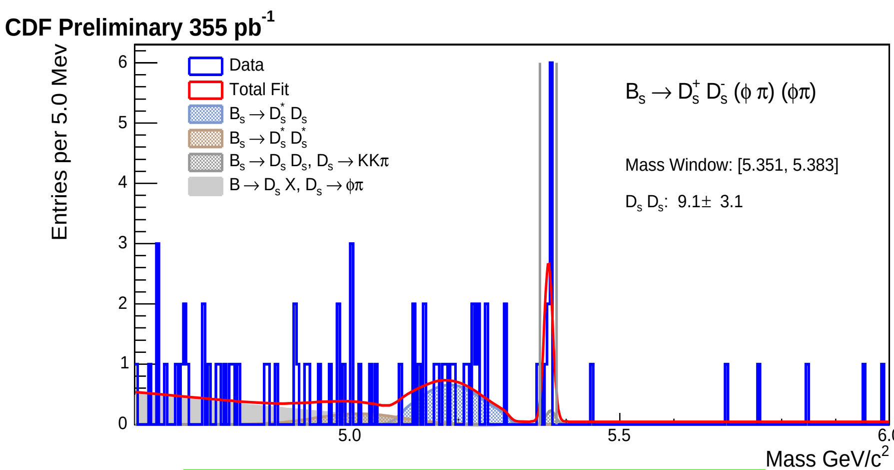
$Br(B_s^0 \to D_s^+ D_s^-)$

Full reconstruction:



B_s^0 D_s^- D_s^+

with $D_s \to \phi\pi,\ KK^*,\ \pi\pi\pi$

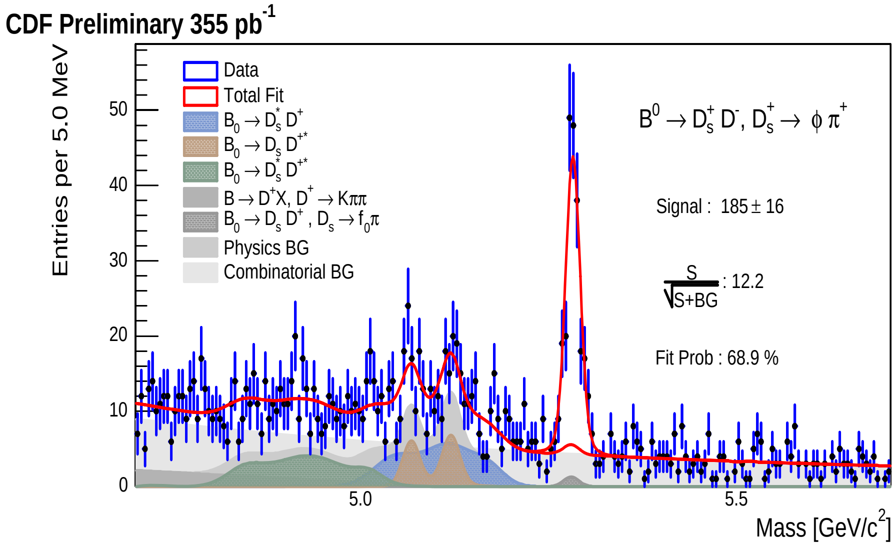


23.5±5.5 total candidates

First observation of this fully reconstructed decay mode

Normalization:

$$B_s^0 \to D_s(\phi\pi, KK^*, \pi\pi\pi) + D(K\pi\pi)$$

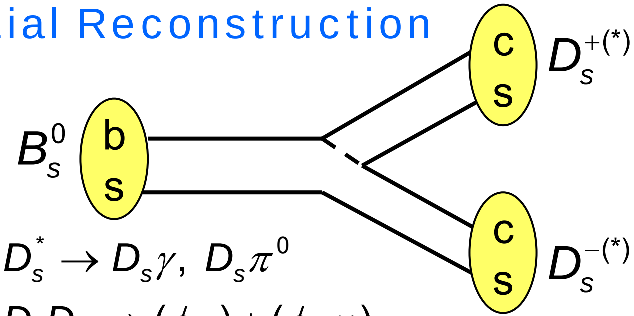


$$\frac{Br(B_s^0 \to D_s^+ D_s^-)}{Br(B_s^0 \to D_s^\pm D^\mp)} =$$

$$1.67 \pm 0.41(stat) \pm 0.12(syst) \pm 0.24(f_s/f_d) \pm 0.39(Br_{\phi\pi})$$

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

Partial Reconstruction



$D_s^* \to D_s\gamma,\ D_s\pi^0$

$D_s D_s \to (\phi\pi) + (\phi\mu\nu)$

(γ and π^0 are not reconstructed)

Inclusive $D_s D_s$, $D_s D_s^*$, $D_s^* D_s^*$ analysis

Normalization

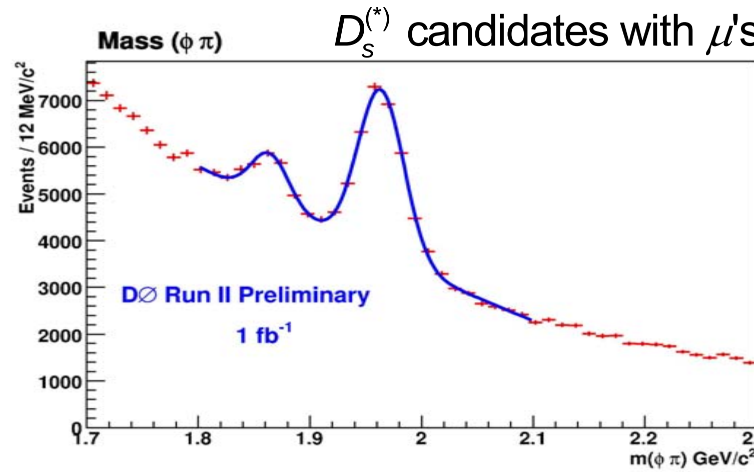
$$B_s^0 \to D_s^{(*)} + \mu\nu \to \phi\pi + \mu\nu$$

Measure the relative rate

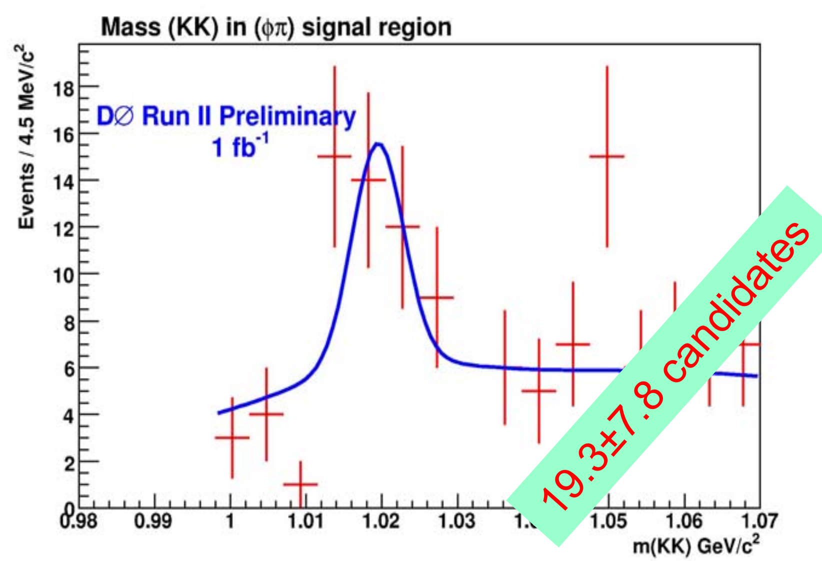
$$R = \frac{Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) \cdot Br(D_s \to \phi\mu\nu)}{Br(B_s^0 \to D_s^{(*)}\mu\nu)}$$

$$Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) = 0.071 \pm 0.032(stat)^{+0.029}_{-0.025}(syst)$$

Since $D_s^{(*)} D_s^{(*)}$ is a CP eigenstate, this decay mode can be used to measure $\Delta\Gamma_{CP}$.



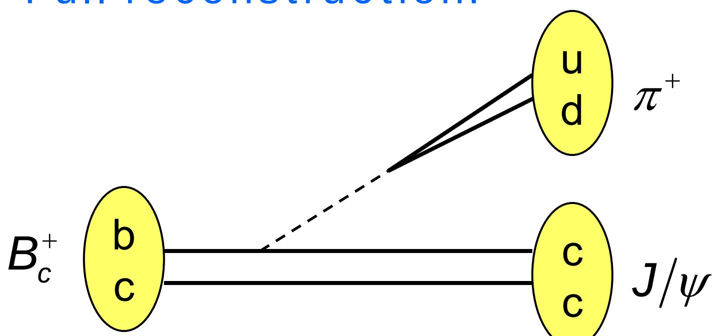
search for another ϕ…

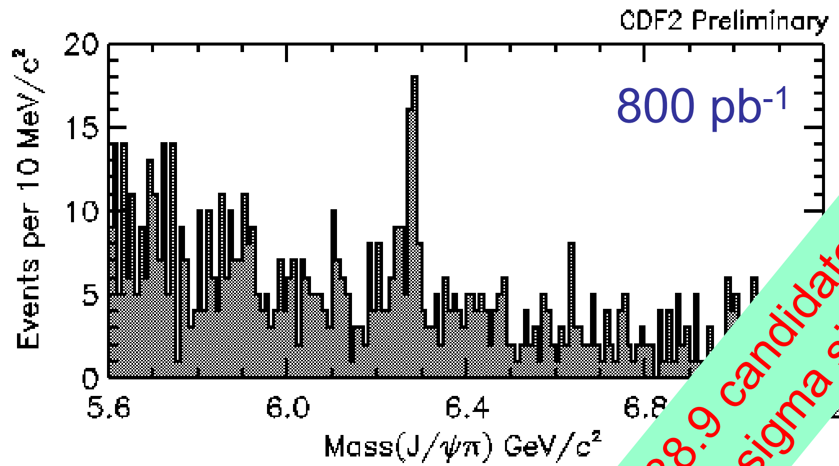


Bc Mass

A (bc) bound state, unique (qq) system with two heavy quarks
Not produced at B factories, rarely produced at Tevatron

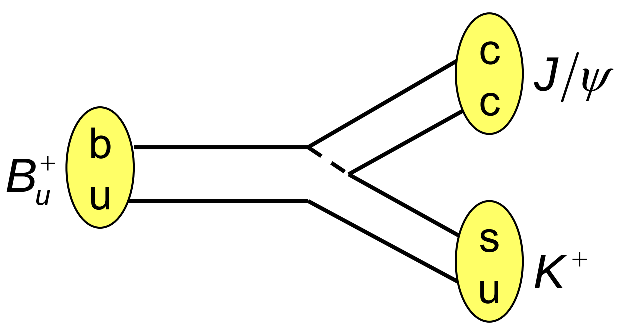
Full reconstruction:





38.9 candidate events
>6 sigma significance!

Bu→ J/ψ K as benchmark



B_c mass =
$6275.2 \pm 4.3(stat) \pm 2.3(syst)$ MeV/c^2

World's Best !

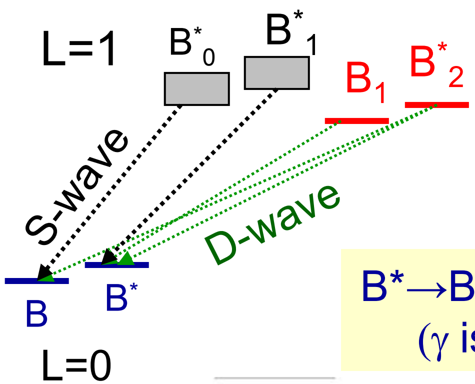
Lattice QCD calculation
$M(B_c) = 6304 \pm 12^{+18}_{-0}$ **MeV/c^2**
(Allison et al, PRL 94, 172001 (2005))

B_J^* (B^{**}) Mesons

Four L=1 states of (bd) system

two broad (~100 MeV) and

two narrow (~10 MeV) resonances



$B_1 \rightarrow B^* + \pi$,

$B_2^* \rightarrow B^* + \pi$,

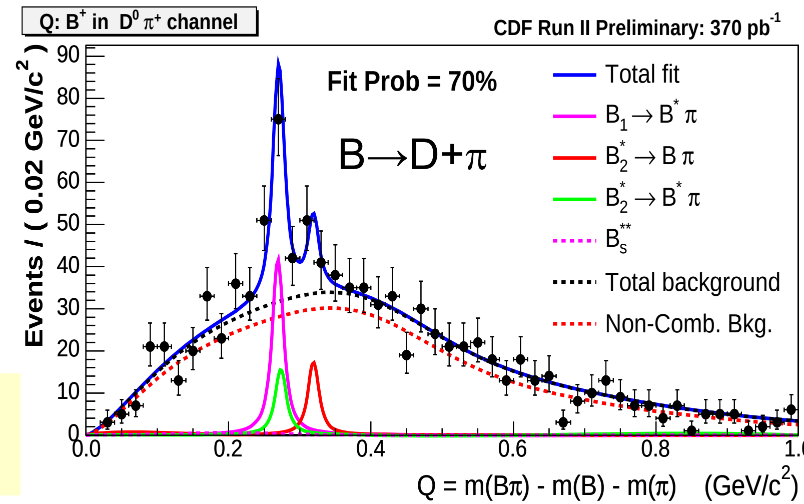
$B_2^* \rightarrow B + \pi$

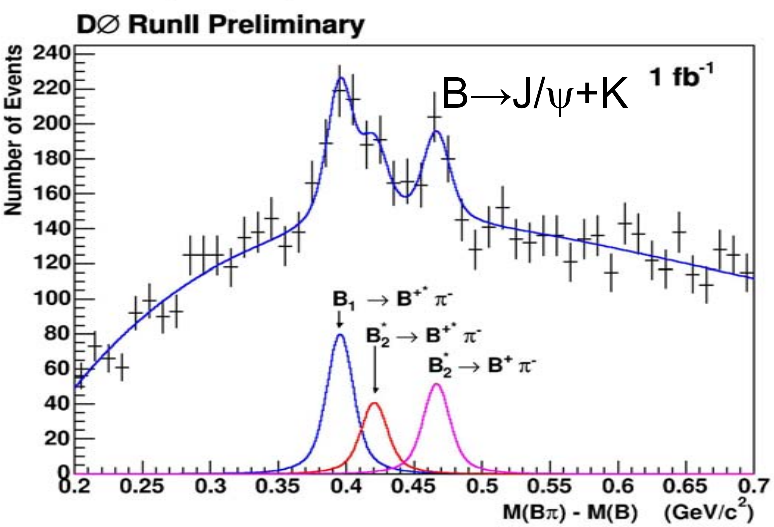
with

$B^* \rightarrow B + \gamma$ and $B \rightarrow J/\psi + K$, $D + \pi$

(γ is not reconstructed)

Identification of narrow resonances





CDF

$$M(B_1) = 5734 \pm 3 \pm 2 \ \mathrm{MeV}/c^2$$

$$M(B_2^*) = 5738 \pm 5 \pm 1 \ \mathrm{MeV}/c^2$$

DØ

$$M(B_1) = 5720.8 \pm 2.5 \pm 5.3 \ \mathrm{MeV}/c^2$$

$$M(B_2^*) - M(B_1) = 25.2 \pm 3.0 \pm 1.1 \ \mathrm{MeV}/c^2$$

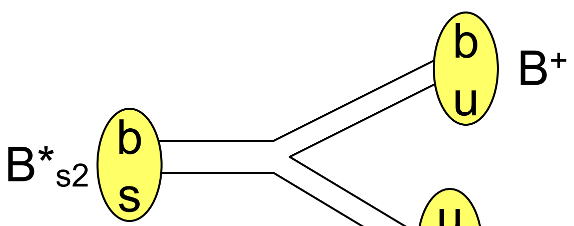
$$\Gamma(B_2^*) = \Gamma(B_1) = 6.6 \pm 5.3 \pm 4.2 \ \mathrm{MeV}$$

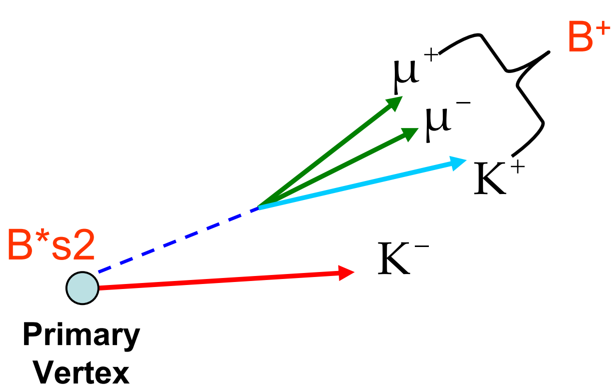
B_{s2}* Meson

Similar to B states, the quark model predicts 4 P-states for (bs) system. B*$_{S2}$ is the counterpart of B*$_2$.**

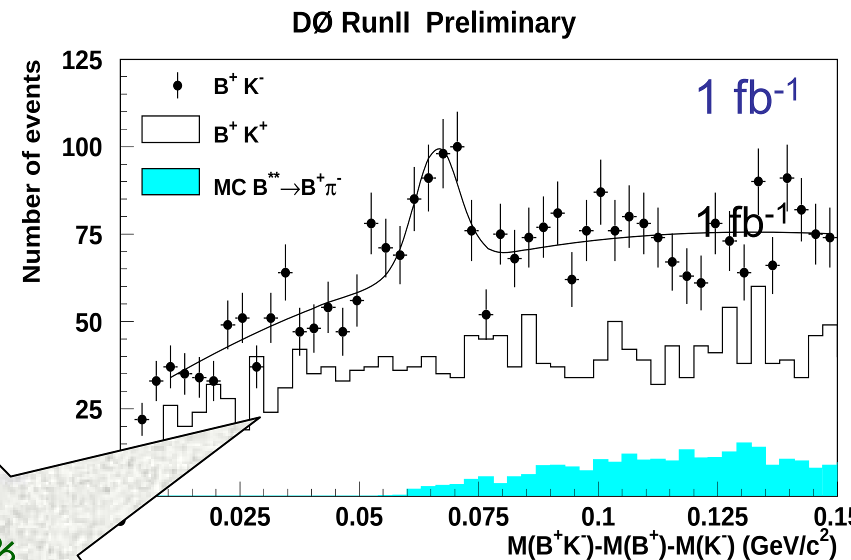
Full Reconstruction

$$B^*_{s2} \rightarrow B^+ + K^- \text{ with } B^+ \rightarrow J/\psi + K^+$$





Mass difference: M(B⁺K⁻)-M(B⁺)-M(K⁻)



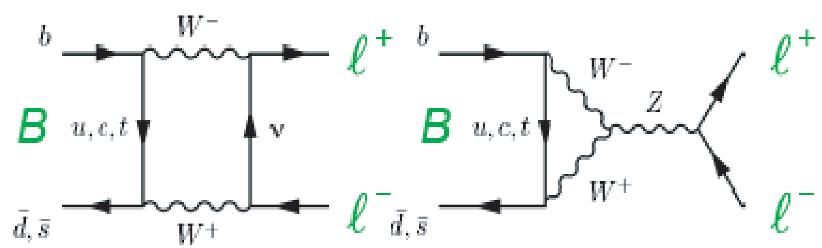
M(B*$_{s2}$) = 5839.1 ± 1.4±1.5 MeV

135±31 candidates

First direct observation with 5 sigma !

FCNC Rare Decays

The flavor changing neutral current interaction is forbidden at tree-level in SM, but can occur through loop diagrams such as those at the right



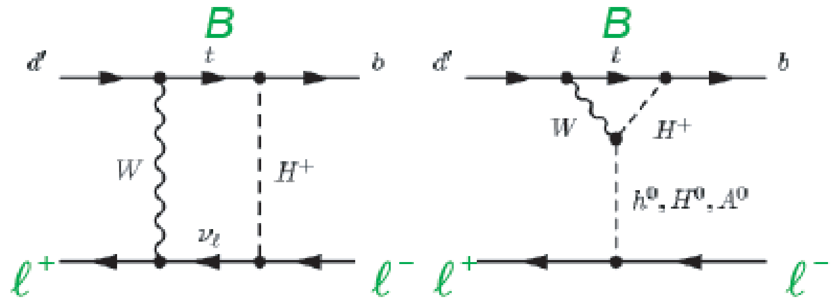
However, the rate is further suppressed by helicity conservation for light leptons. The estimated rate are

$$Br(B_s^0 \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$$

$Br(B_d^0 \to \mu^+\mu^-)$ is further suppressed

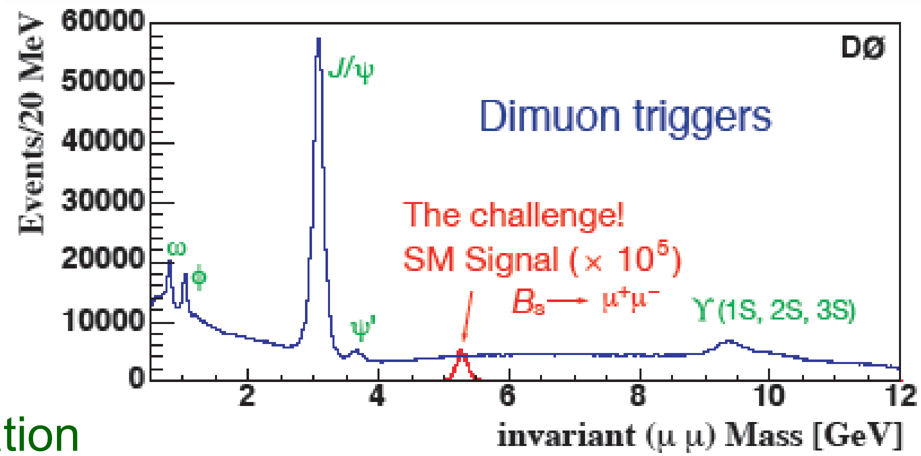
by factor of $\left|V_{td}/V_{ts}\right|^2 \approx 0.04$.

In MSSM, additional contributions are expected, the branching ratio is expected to grow as $\tan^4\beta$ or $\tan^6\beta$, ideal for probing indirect probing of new physics



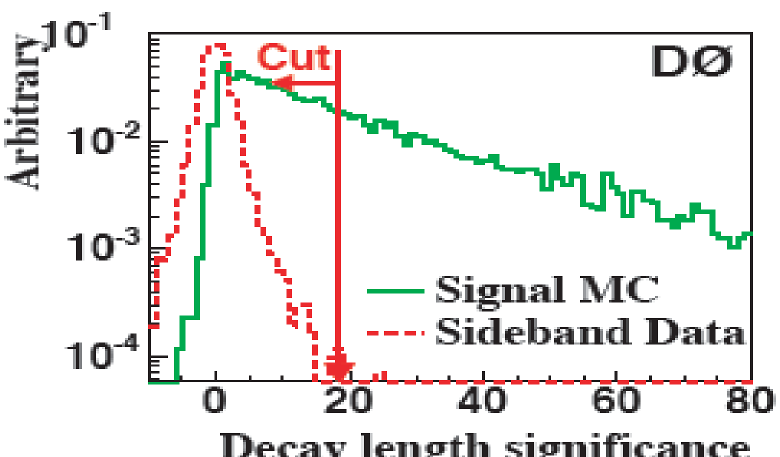
$B_d^0, B_s^0 \to \mu^+\mu^-$

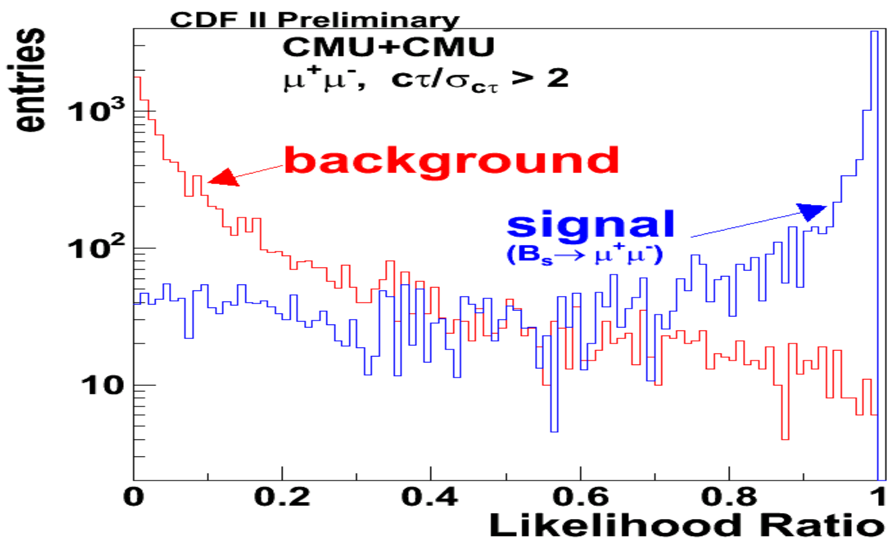
Large continuum μμ background
- Drell-Yan
- semileptonic decays
  - *e.g.* b→μcX, c→μX
- fakes



Exploit kinematics
- decay length, pointing angle, isolation

DØ cuts on these variables directly while CDF cuts on the likelihood

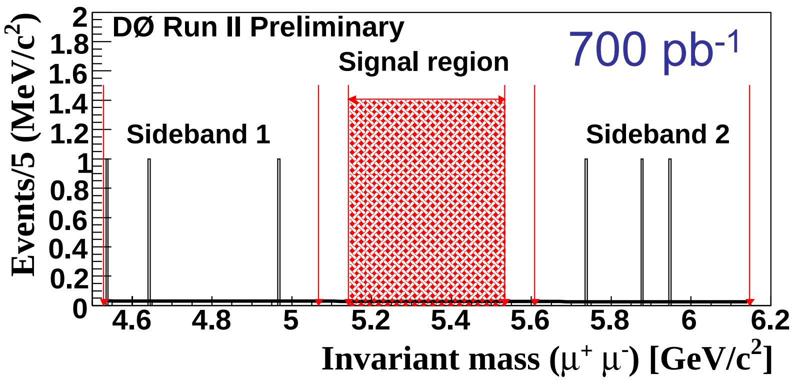


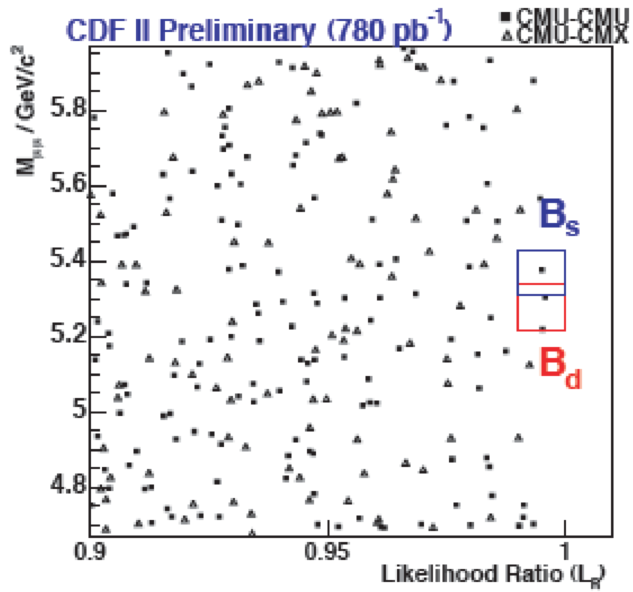


Both experiment pursue blind analysis

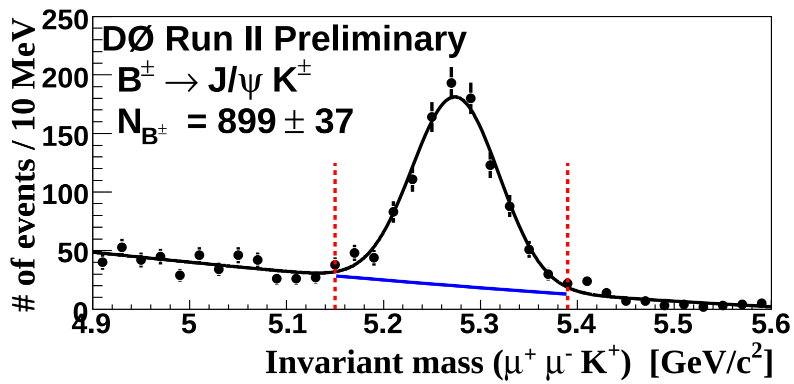
$B_d^0,\ B_s^0 \to \mu^+\mu^-$

Sidebands to model backgrounds





B±→J/ψ K± for normalization



CDF: (actual limit @ 95% CL)

$$Br(B_d^0 \to \mu^+\mu^-) < 3.0\times10^{-8}$$

$$Br(B_s^0 \to \mu^+\mu^-) < 1.0\times10^{-7}$$

(DØ does not have the mass resolution to separate Bd and Bs states)

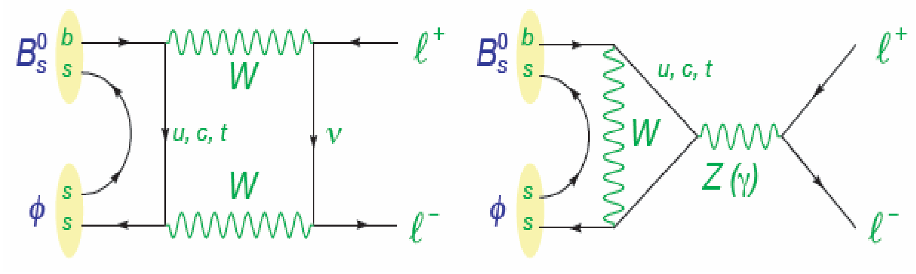
DØ sensitivity @ 95% CL

$$Br(B_s^0 \to \mu^+\mu^-) < 2.3\times10^{-7}$$

about a factor of 50 away from the standard model expectation

$B_s^0 \rightarrow \mu^+\mu^-\phi$

Expected from loop diagrams in the standard model. Estimated rate: $Br(B_s^0 \rightarrow \phi\mu^+\mu^-) \sim 1.6 \times 10^{-6}$

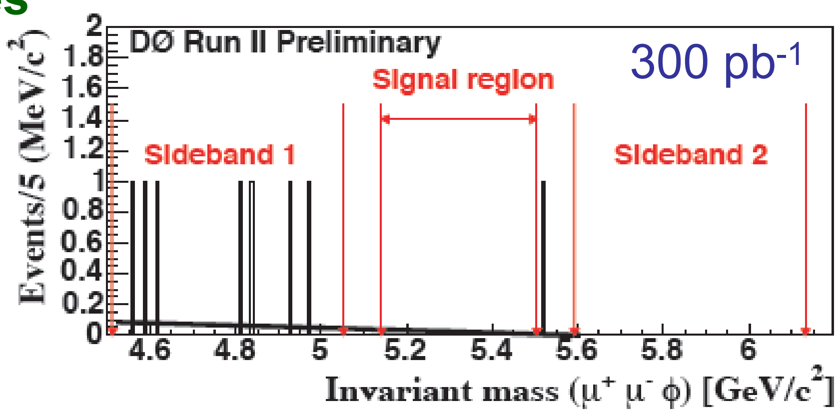


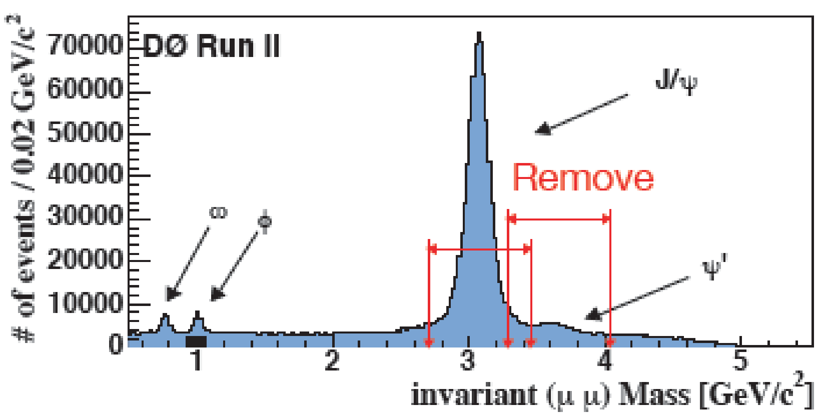
Potential enhancement from new physics.

No events observed in the signal region, using side band to estimate backgrounds

Use the same discrimination variables as the $B_s \rightarrow \mu^+\mu^-$ **analysis.**

Remove events with μμ from J/ψ and ψ' resonances





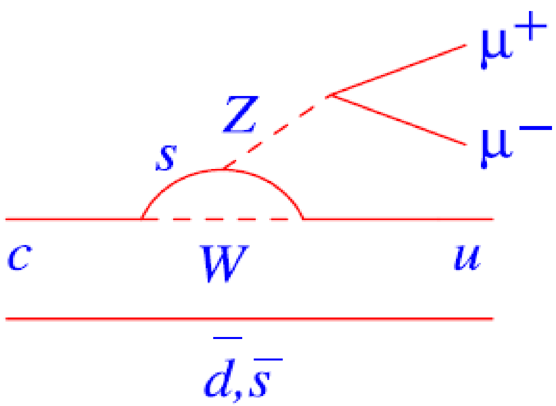
$Br(B_s^0 \rightarrow \mu^+\mu^-\phi) < 4.1 \times 10^{-6}$ @ 95% CL

Only a factor of 3 away from the SM value!

$D^+ \to \mu^+\mu^-\pi^+$

Strict experimental limits on FCNC transitions for down-type quarks
$b \to s,\ s \to d$
relatively weak limit on FCNC transition involving up-type quarks

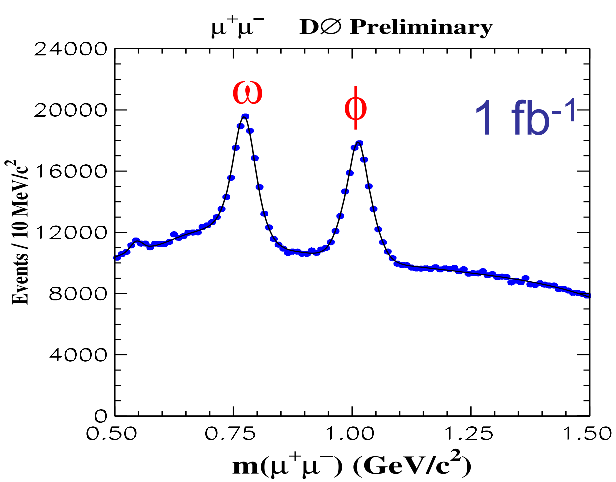
$D^+ \to \mu^+\mu^-\pi^+$ decay is expected from FCNC $c \to u$ transition



with small $Br \sim 10^{-8}$ ...

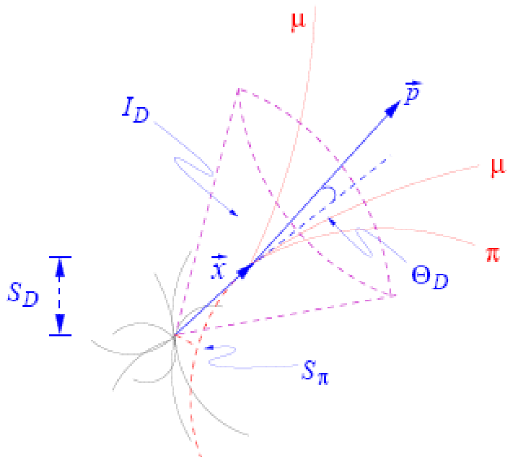
But enhancement is expected from physics beyond standard model

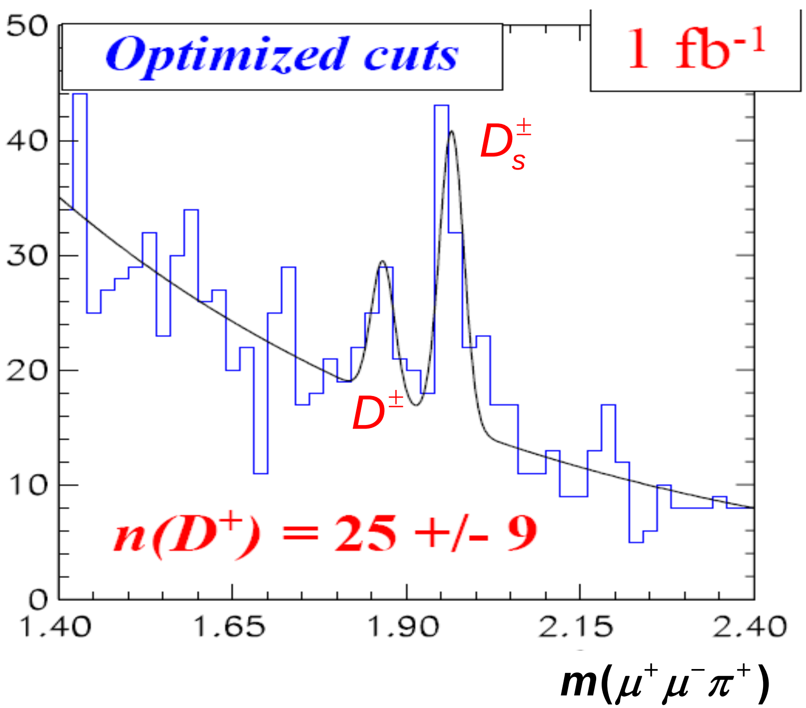
Background from resonance production:
$D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$,
$D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$



However
$m_{\mu\mu} \neq m_\phi$ for $c \to u$ transition!

$D^+ \to \mu^+\mu^-\pi^+$





- $D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ **(resonance):** $0.96 \le m_{\mu\mu} \le 1.06$ **GeV/c²**

Normalize to
$D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$

$$Br(D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+) = (1.75 \pm 0.70 \pm 0.50) \times 10^{-6}$$

CLEO: $(2.7^{+3.6}_{-1.8} \pm 0.2) \times 10^{-6}$

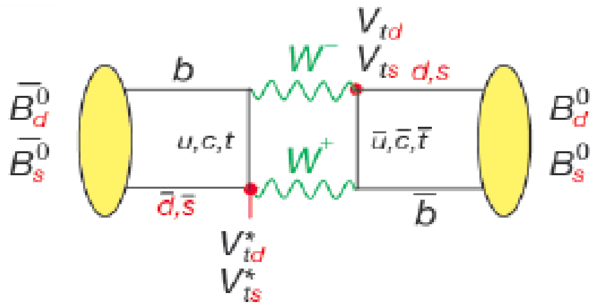
- $D^+ \to \mu^+\mu^-\pi^+$ **(continuum):** $m_{\mu\mu} \le 0.96$ **or** $m_{\mu\mu} \ge 1.06$ **GeV/c²**

17 events observed with 20.9 ± 3.4 expected

$$Br(D^+ \to \mu^+\mu^-\pi^+) < 4.7 \times 10^{-6} \text{ @ 90\% CL}$$

B^0_s Mixing & Decays

The box diagram like the one below and common decay modes of B^0_s and $\bar{B}^0_s$ such as $B^0_s, \bar{B}^0_s \to J/\psi\,\phi$ lead to mass matrix



$$i\frac{d}{dt}\begin{pmatrix} B^0_s \\ \bar{B}^0_s \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M^*_{12} - \frac{i\Gamma^*_{12}}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B^0_s \\ \bar{B}^0_s \end{pmatrix}$$

$$CP = +1: \quad |B_H\rangle = \frac{1}{\sqrt{2}}\left(|B^0_s\rangle + |\bar{B}^0_s\rangle\right)$$

$$CP = -1: \quad |B_L\rangle = \frac{1}{\sqrt{2}}\left(|B^0_s\rangle - |\bar{B}^0_s\rangle\right)$$

The two mass eigenstates have small differences in mass and decay width

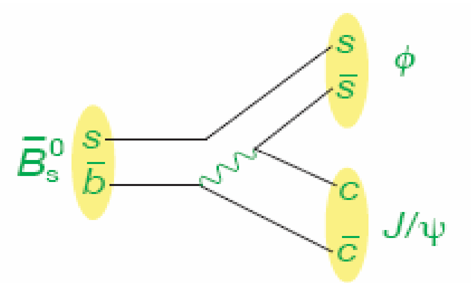
$$\Delta m_s = M_H - M_L = 2|M_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\varphi$$

$\Rightarrow$ $\varphi = 0.3^\circ$ in SM $\Rightarrow$ **mass and CP eigenstates are largely identical**

$\Delta\Gamma_s$ can be measured by studying $B^0_s, \bar{B}^0_s \to J/\psi\,\phi$ decays since both $|B_H\rangle$ and $|B_L\rangle$ are inolved in the decay

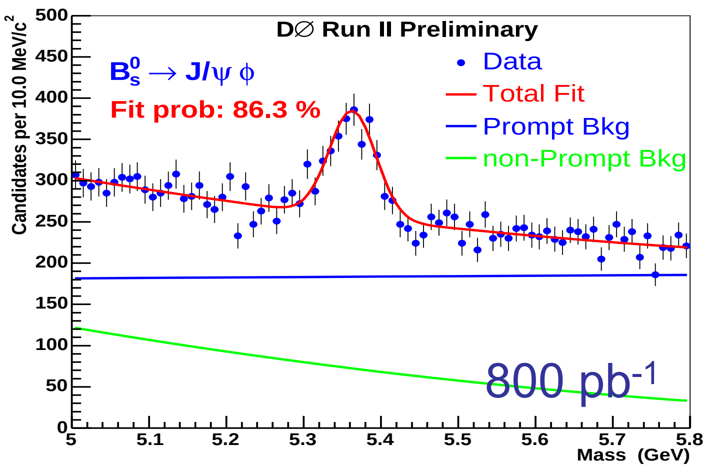
$$B^0_s \to J/\psi\,\phi$$
$$\bar{B}^0_s \to J/\psi\,\phi$$

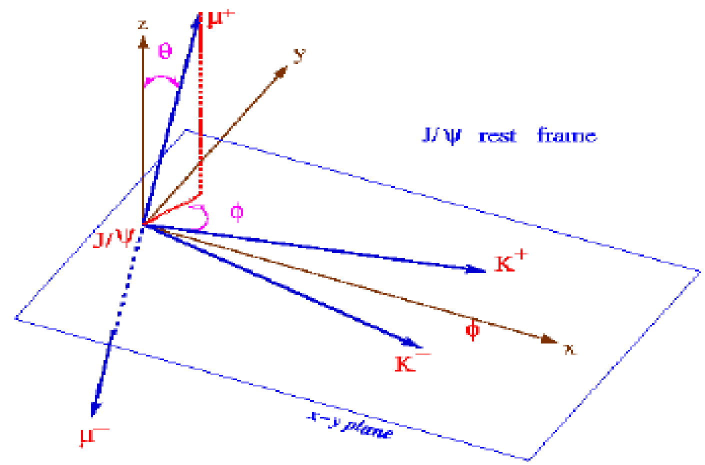


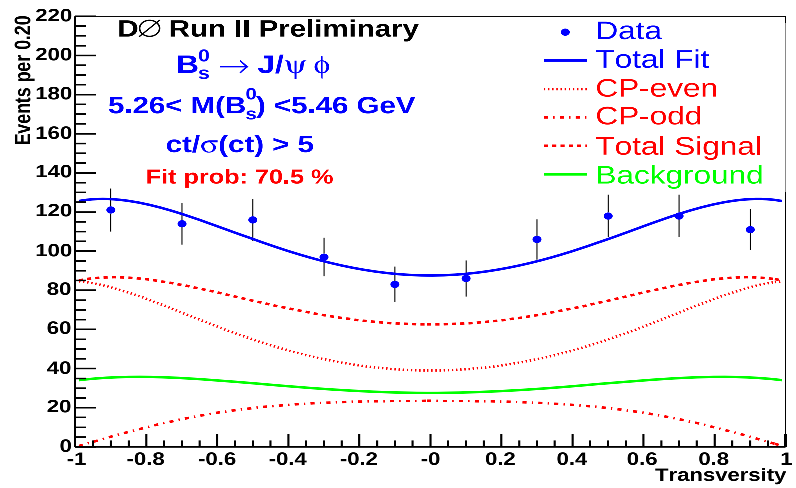
B_s Lifetime Difference

Full Bs →J/ψ ϕ Reconstruction

$$J/\psi \rightarrow \mu^+\mu^- \text{ and } \phi \rightarrow K^+K^-$$







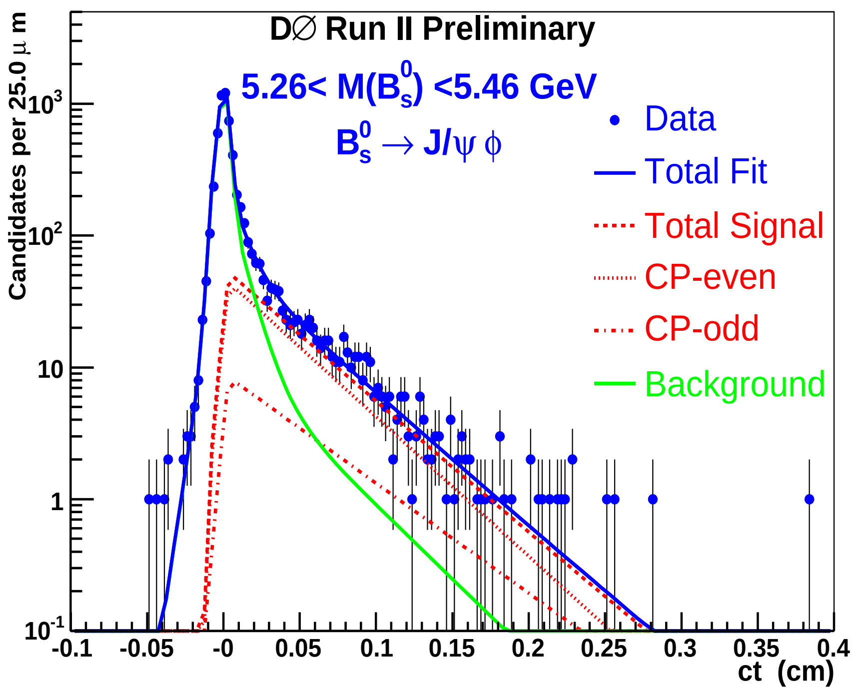
(cosΘ)

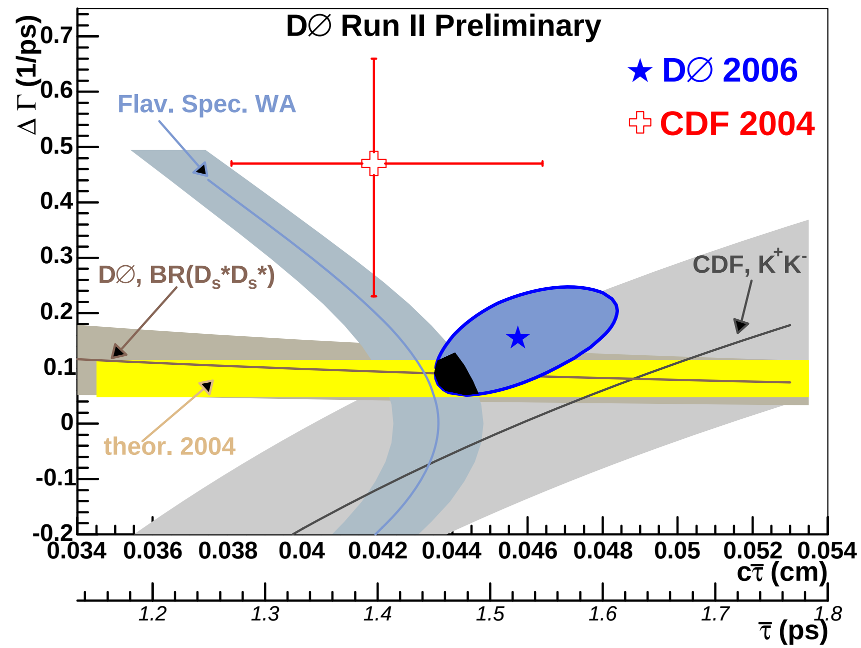
CP-even and CP-odd components are expected to have different angular distributions of the decay particles

Simultaneous fits to distributions of angles and the decay length to extract lifetimes of the two mass (and CP) eigenstates

B_s Lifetime Difference

Different lifetimes for the two mass eigenstates in the decay length fit





$$\bar{\tau}_{B_s} = \frac{\tau_H + \tau_L}{2} = 1.53 \pm 0.08^{+0.01}_{-0.03} \text{ ps}$$

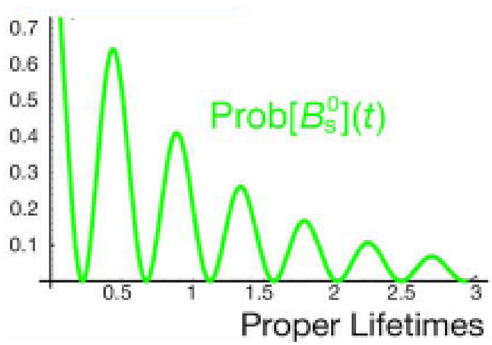
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.15 \pm 0.10^{+0.03}_{-0.04} \text{ ps}^{-1}$$

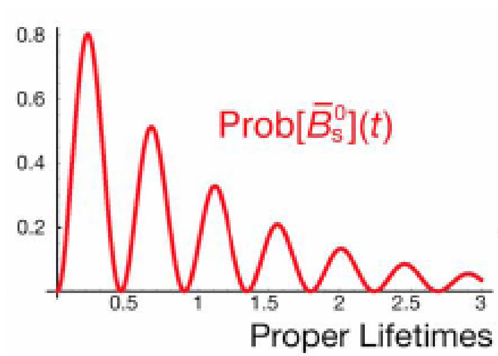
B^0_s Oscillations

For an initial B^0_s

$$\text{Prob}(B_s^0 \to B_s^0)(t) = \frac{1}{4}\left(e^{-\Gamma_H t} + e^{-\Gamma_L t} + 2e^{-\Gamma t}\cos(\Delta m_s t)\right)$$

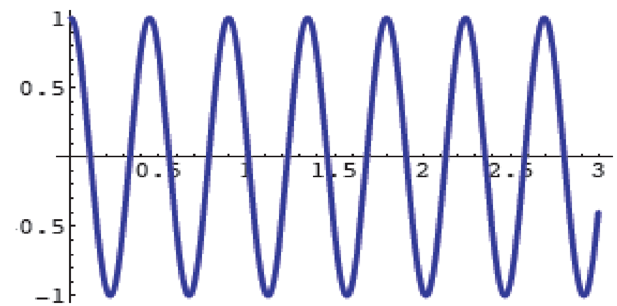
$$\text{Prob}(B_s^0 \to \bar{B}_s^0)(t) = \frac{1}{4}\left(e^{-\Gamma_H t} + e^{-\Gamma_L t} - 2e^{-\Gamma t}\cos(\Delta m_s t)\right)$$





Asymmetry:

$$A = \frac{N(B_s^0) - N(\bar{B}_s^0)}{N(B_s^0) + N(\bar{B}_s^0)} \propto \cos(\Delta m_s t)$$

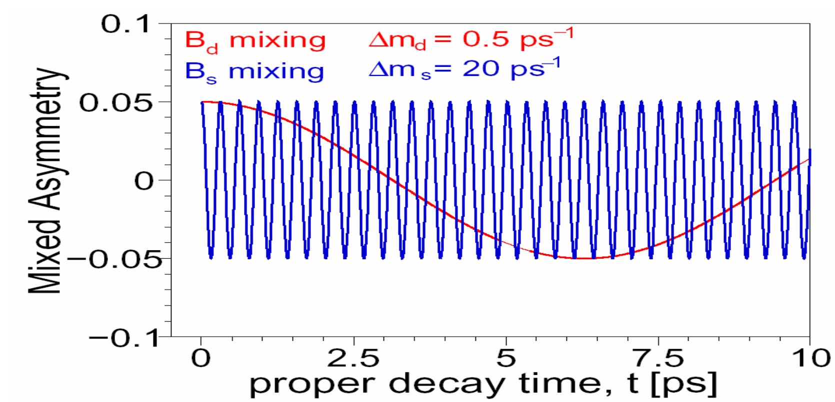


Compared with B^0_d oscillation:

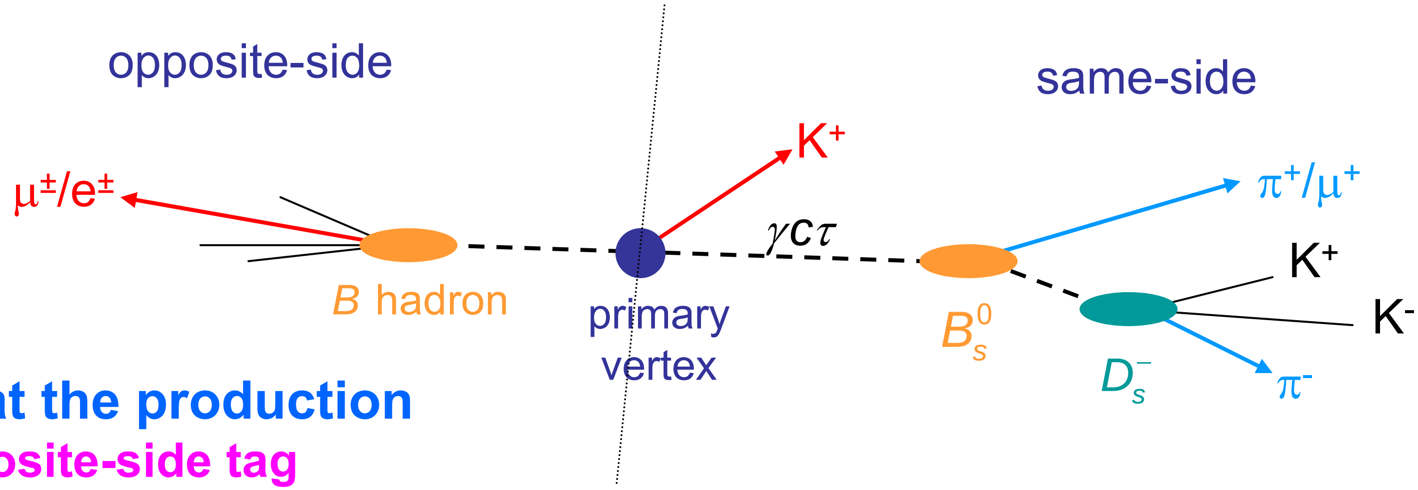
$$\Delta m_s \propto \left|V_{tb}^* V_{ts}\right|^2 \;\sim>>\; \Delta m_d \propto \left|V_{tb}^* V_{td}\right|^2$$

B_s^0 oscillates much fast!

World Average Limit
$\Delta m_s > 14.4$ ps^{-1}



Analysis Technique



Flavor at the production

- **opposite-side tag**
  - **lepton from the other b decay**
  - **jet charge**

  (CDF: εD^2=1.5%, D∅ : εD^2=2.5%)
- **same-side tag**
  - **kaon from fragmentation**

  (CDF: $\varepsilon D^2 \sim 3.5\%, 4.0\%$)

Tagging power: εD^2

- **ε is tagging efficiency**
- **$D = 1 - 2w$: dilution**

  w: wrong tag probability

Decay proper time

- **decay length (vertices)**
- **boost correction (momentum)**

Flavor at the decay

- **Full reconstruction:**

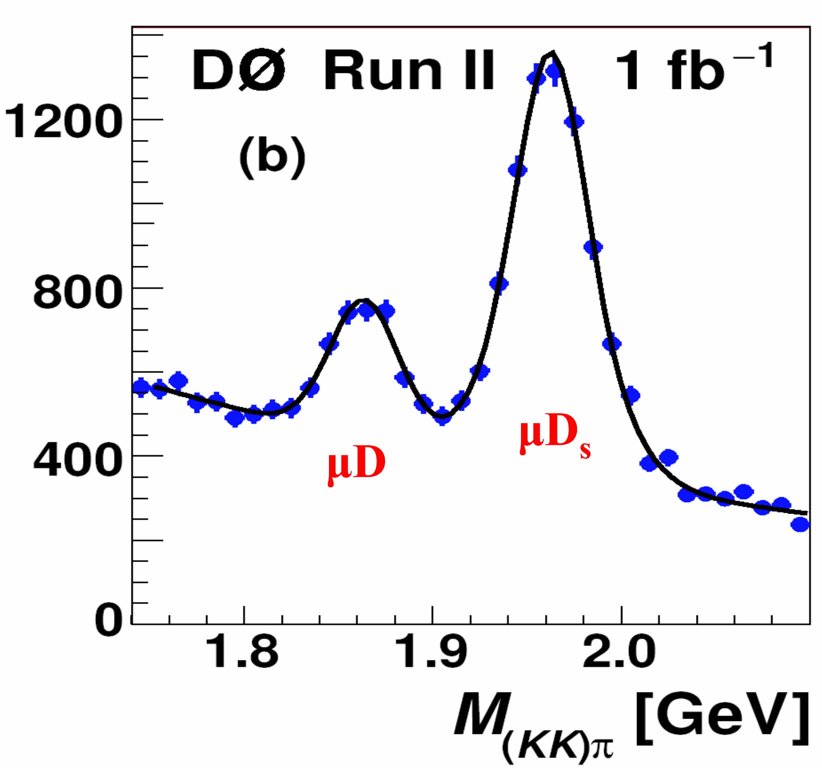
  $B_s^0 \to \pi^+ D_s^-$ **($\sigma_{c\tau}$~90 fs)**
- **Partial reconstruction:**

  $B_s^0 \to \ell^+ \nu D_s^-$ **($\sigma_{c\tau}$~150 fs)**

B^0_s Reconstruction

DØ: semileptonic B_s decay only

$$B_s^0 \to \mu^+ D_s^- + X \to \mu^+ \phi \pi^- + X$$



5,600 tagged μD_s events

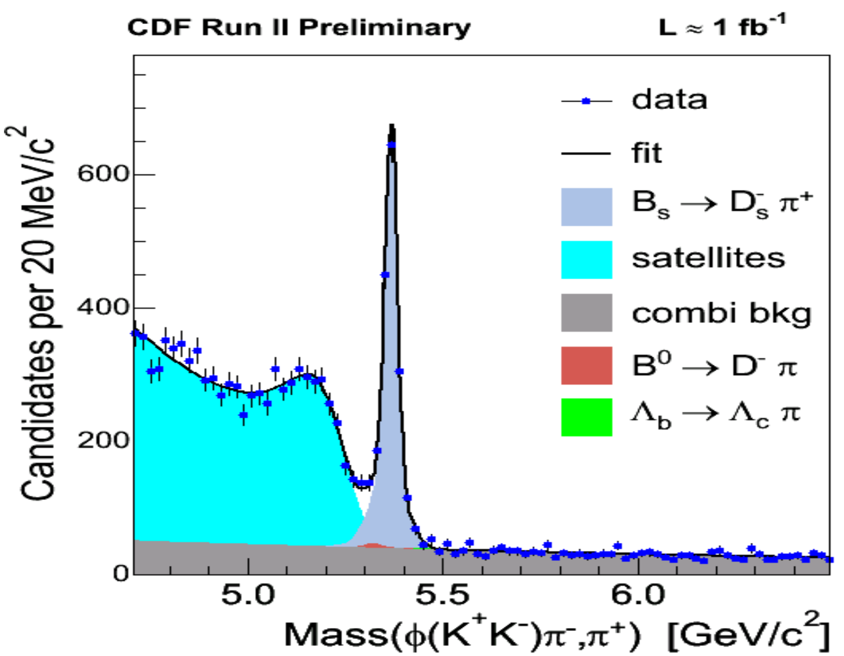
~20% tagging efficiency

~85% μD_s events are "signal"

CDF: Bs in both semileptonic and hadronic decays

$$B_s^0 \to \pi^+ D_s^-;\ B_s^0 \to \ell^+ \nu D_s^-;\ \ldots$$

with $D_s \to \phi\pi, K^* K, \pi\pi\pi$



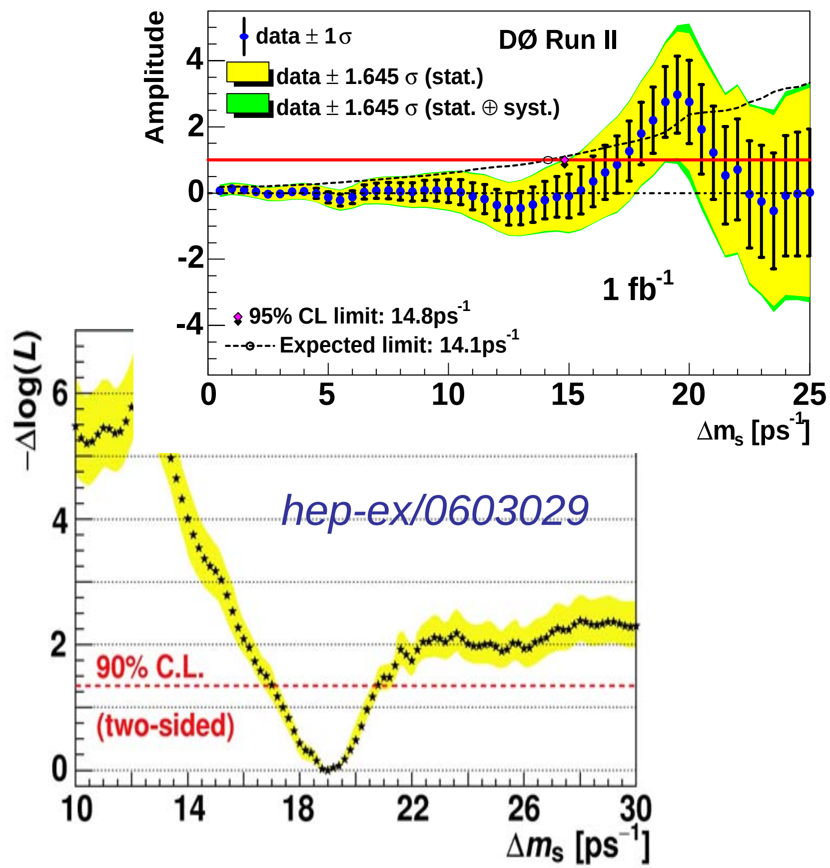
Events: 3,600 in hadronic mode

37,000 in leptonic mode

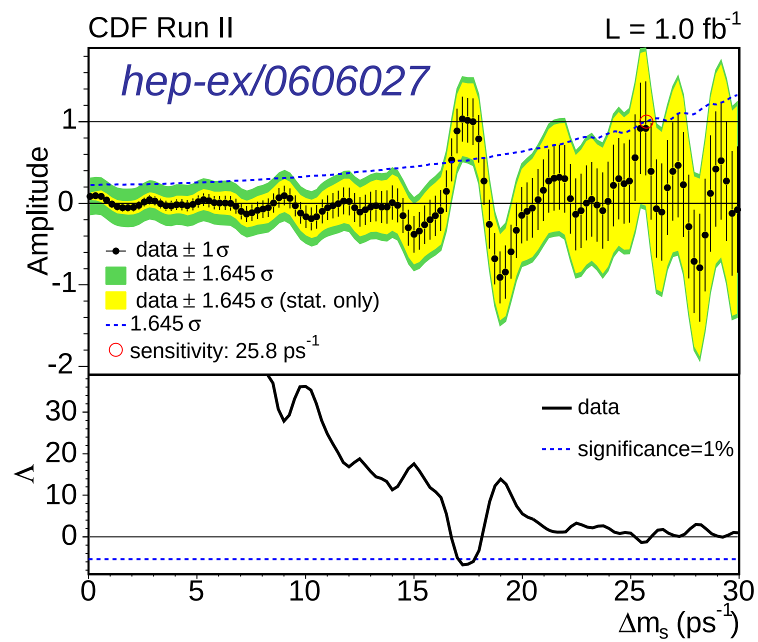
Oscillation Frequency

$$P^{osc./no-osc.} = \frac{\Gamma}{2} e^{-\Gamma \cdot t} \cdot \left(1 \pm D \cdot \cos\left(\Delta m_s \cdot t\right) \cdot \mathcal{A}\right)$$

$\mathcal{A}=1$: oscillation
$\mathcal{A}=0$: no oscillation



Deviation from A=0:
DØ: at 2.5 sigma
CDF: at 3.7 sigma



$17 < \Delta m_s < 21 \, ps^{-1}$ @ 90% CL

$\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07 \ ps^{-1}$

Summary

- Many new results on masses, lifetimes and decay branching ratios of B hadrons from 1 fb^{-1} dataset.
- Sensitivities of rare decays are approaching Standard Model predictions, expected to observe some of them in Run II
- First measurement of Bs oscillation frequency. Golden opportunity for careful studies of Bs system.
- Too many interesting heavy flavor results from Tevatron, impossible to cover them all. People interested are suggested to visit CDF and DØ B physics web pages:
  CDF: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
  DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm
- New results from increasingly large datasets are expected over the next few years.