# B Physics at the Tevatron


**Steve Nahn-Yale University/CDF**

**Ambassador for the CDF and DØ Collaborations**


**Mandate:** *"..The invited session talks are 30+6 minute review talks designed to highlight and advertise the many short talks in the contributed sessions"*

*"many"* = 30 in this case!

# Plan

- **Short Course in Heavy Flavor Physics @ TeV**
  - **Excellent intro by P. Burchat in A0**
- **Heavy Flavor Results Smorgasbord**
  - **Production measurements**
  - **Decays**
  - **Lifetimes and Mixing**

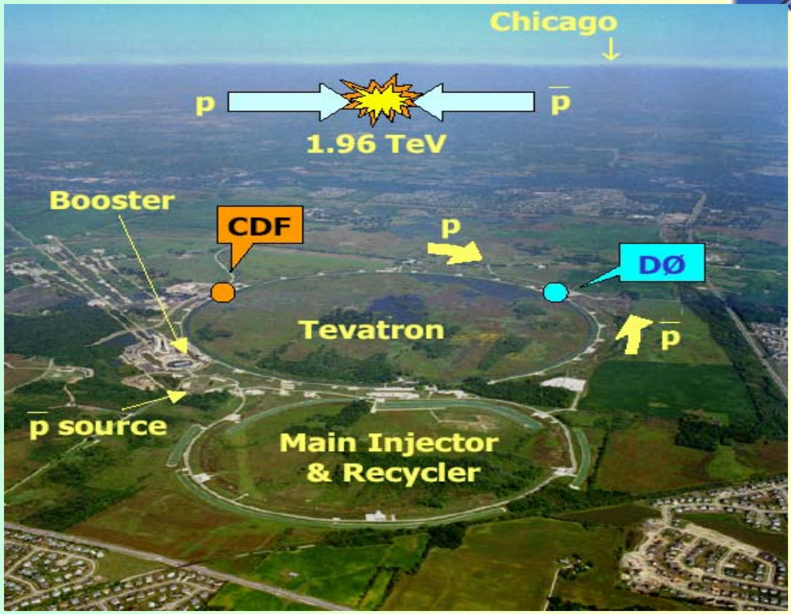
*Highlight* *results presented at APS/DPF `05.*

*•Where* *other results* *exist, not discussed*
*•Attempt at equal exposure for each experiment*
*•Details?* ***GO TO THE SESSIONS!***

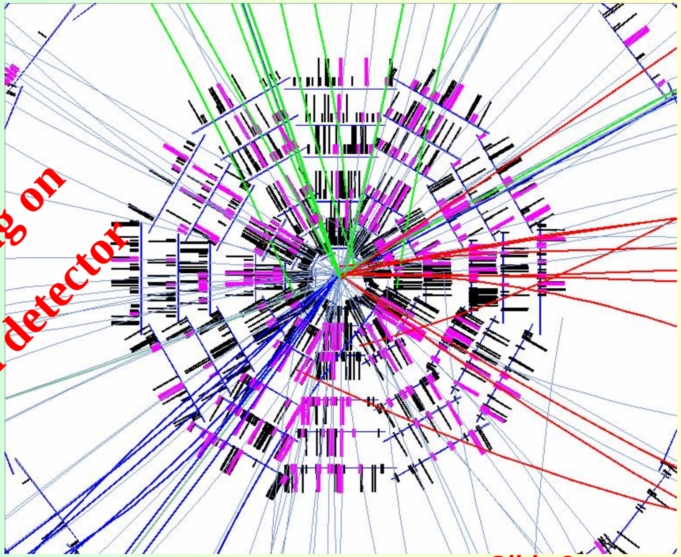
# The Tevatron is a Dirty B factory

- **Wealth of B Physics**
  - $\sigma(p\bar{p} \to bX) \approx 100\,\mu b$

    $\mathcal{L}_{\text{inst}} \sim 100\,\mu b^{-1} s^{-1} \to 10\text{ kHz}$
    - **Only ~5% reconstructable**
  - **Zoo of b hadrons: $B^0$, $B^+$, $B_s$, $B_c$, $\Lambda_b$, $\Xi_b$, B****




- **But**
  - $\sigma(p\bar{p} \to X)$ **$\mathcal{O}(10^3)$ higher**
  - **Hard to find “other b”**
    - **~ 30% acceptance**
  - **Boost not large**

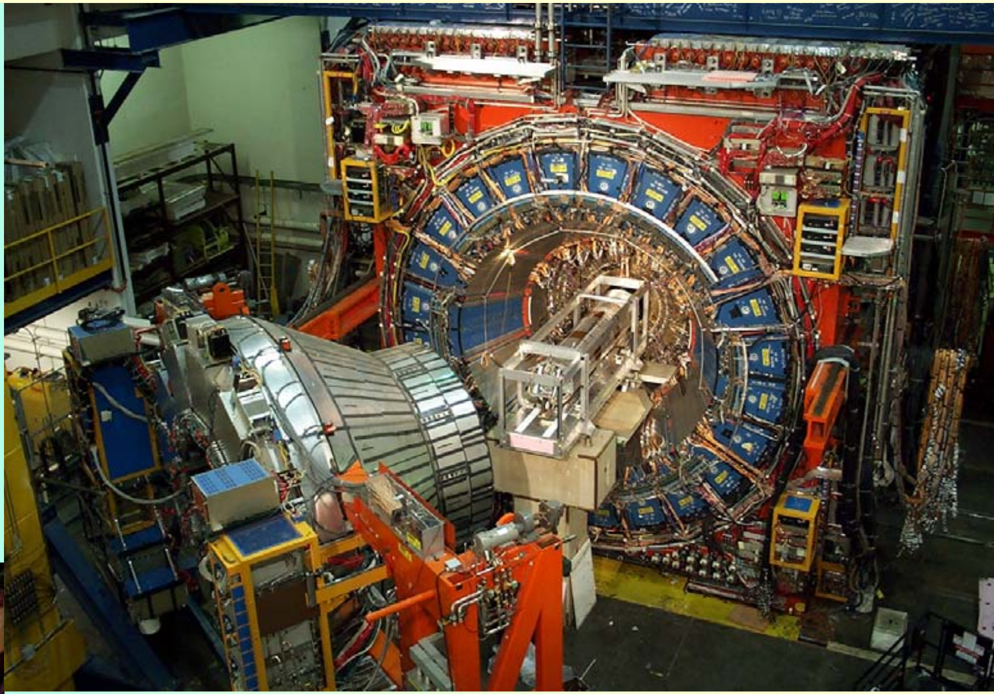


**Lots going on in Si detector**

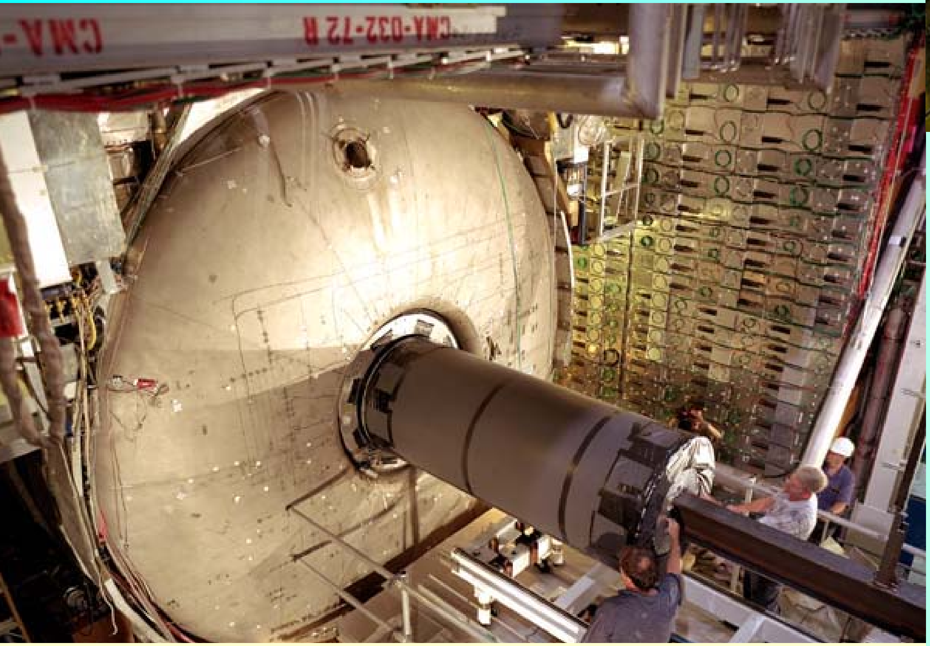
# Detectors

- **Both detectors**
  - Silicon microvertex detectors
  - Central tracking in Solenoid
  - High rate trigger/DAQ system
  - Calorimeter & muon systems
  - Require all-charged final states

CDF silicon detector installation



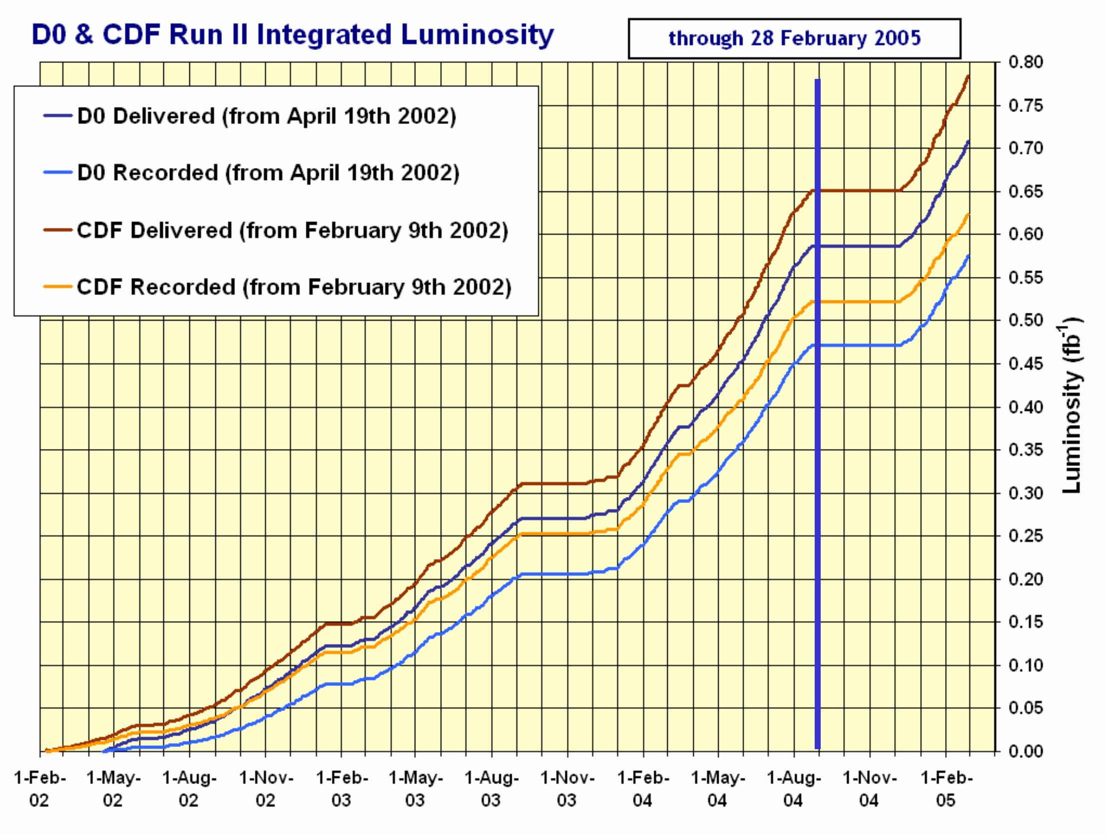
- **DØ**
  - Excellent electron & muon ID
  - Excellent tracking acceptance
- **CDF**
  - Particle ID (TOF and dE/dx)
  - Excellent mass resolution



DØ fiber tracker installation

# Datasets

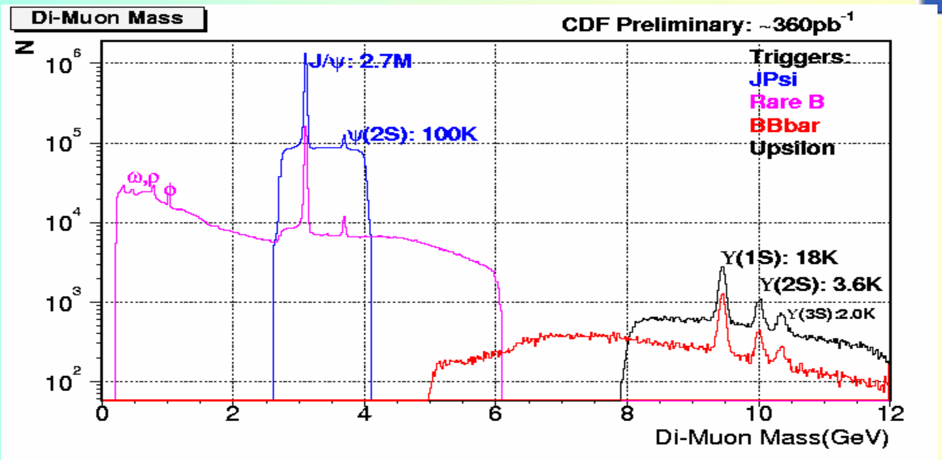
- **After slow start, Tevatron excelling**
  - $d\mathcal{L}_{int}/dt$ **increasing**
- **Data on tape:**
  - **~500 $pb^{-1}$ 2002-2004**
  - **~ +100 $pb^{-1}$ 2005**

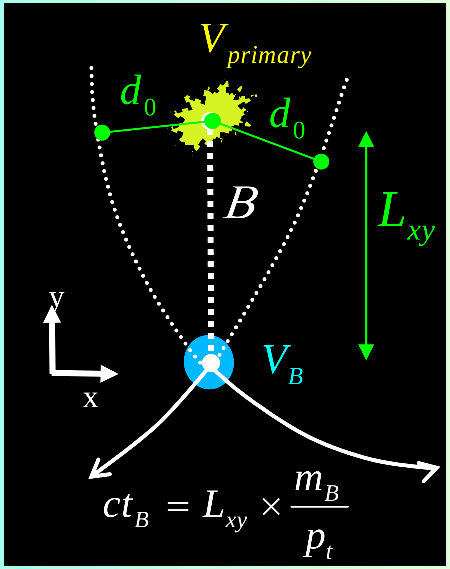


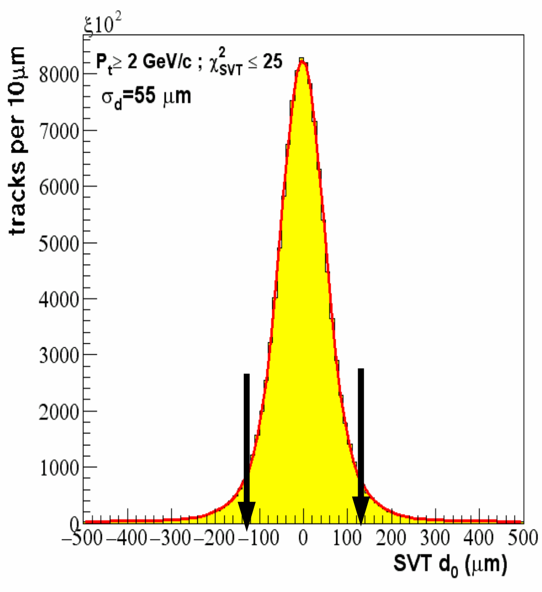

- **DØ:**
  - **~220-500 $pb^{-1}$ in these results**
- **CDF:**
  - **~240-360 $pb^{-1}$ in these results**

# Triggering: Heavy Flavor → Tape

- $H_b \rightarrow X(J/\psi \rightarrow \mu\mu)$
  - 2 track ↔ μ matches within $m_{\mu\mu}$ window
- $H_b \rightarrow l^{\pm}\nu X$
  - Lepton signature in $p_T$ range
- $H_b \rightarrow$ *hadrons*
  - Displaced tracks and vertex



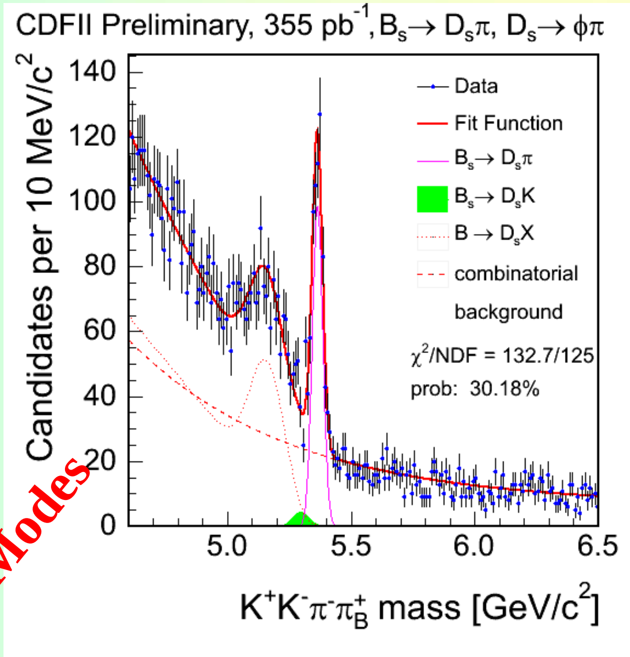



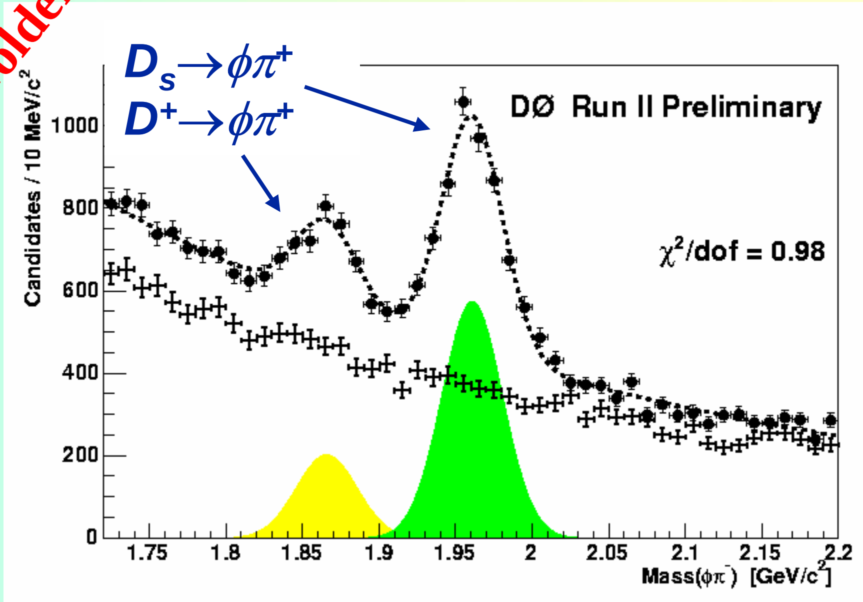



# Heavy Flavor Analysis

- **Selection techniques**
  - Quality objects
  - Kinematics
  - Consistent vertex structure
- **Reference channels**
  - Relative Branching Ratios
  - Calibrate algorithms
  - Optimize Selection
- **Simulation**
  - Detector effects
  - Other resonance pollution
- **Algorithms**
  - Simultaneous likelihood fits
  - PID for statistical separation

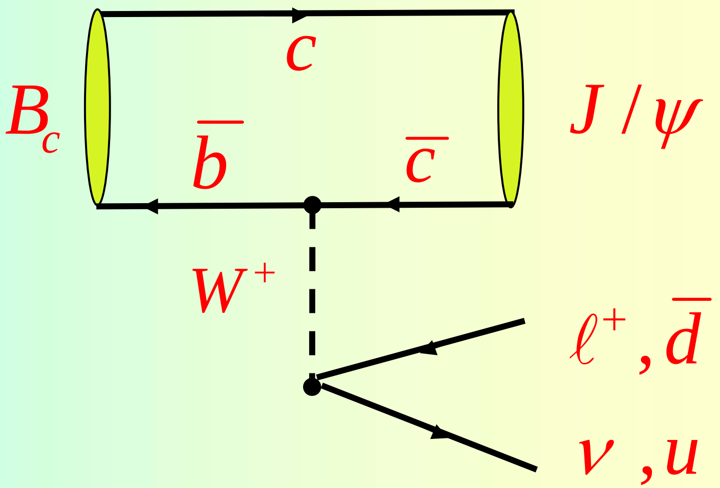
Golden $B_s$ Modes



# Production of $B_c$ Mesons

- **Least well known B meson**
- **Theory: Largest mass, shortest lifetime**
- **20 ± 6 events in Run 1**

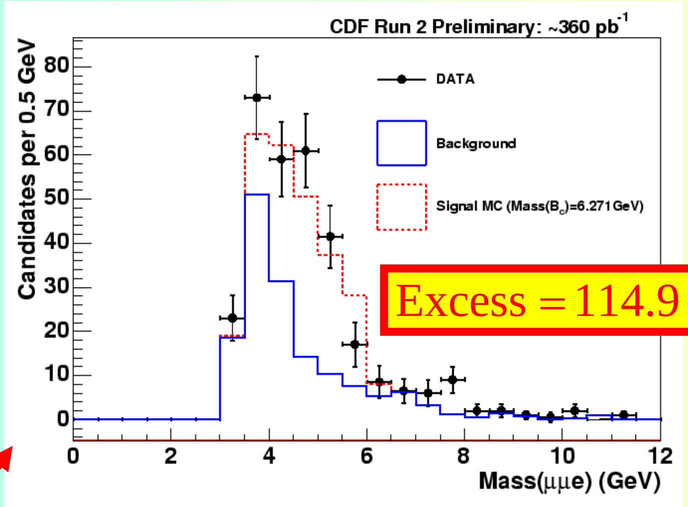



| **PDG 2004** | **$B_c$** | **Compare to $B^0$** |
|---|---|---|
| ***m*** **[GeV/c2]** | **6.4 ± 0.4** | **5.2793 ± 0.0007** |
| **τ [ps]** | **0.46 ± 0.17** | **1.536 ± 0.014** |

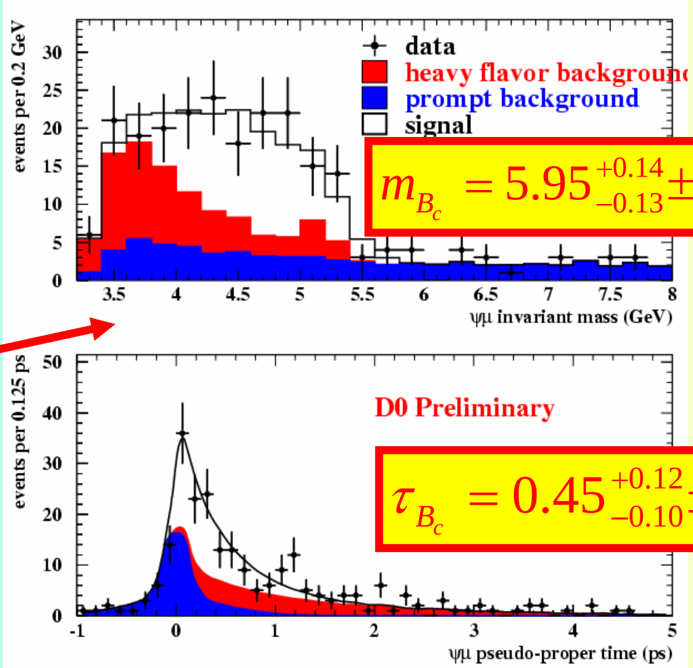
# $B_c \to J/\psi\, l\, \upsilon$

S J8: CDF: Hartz & Aoki DØ: Ay

- **$B \to J/\psi\, K$ as reference**
- **Background suppression KEY**
  - **Fake J/ψ or lepton**
  - **b [→J/ψ] $\bar{b}$ [→ $l$ ]**
- **CDF: separate cross section ratio for $l$ = μ ,e**
  - **Combined lifetime next**
- **DØ: mass and lifetime in μ**
  - **Moving to $B_c \to J/\psi\, \pi$**




$\text{Excess} = 114.9 \pm 15.5 \pm 13.6$

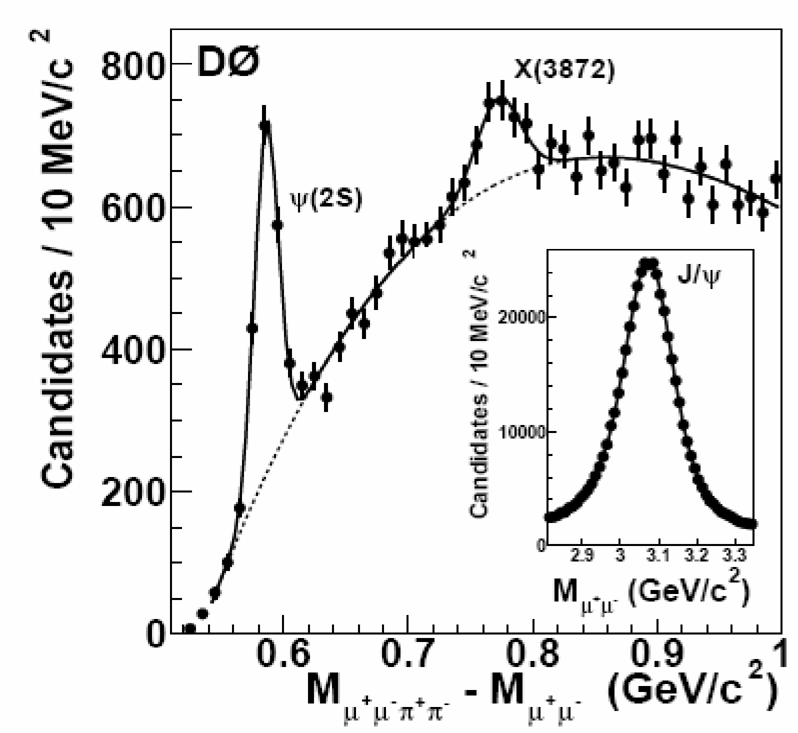



$m_{B_c} = 5.95^{+0.14}_{-0.13} \pm 0.34\, GeV/c^2$

$\tau_{B_c} = 0.45^{+0.12}_{-0.10} \pm 0.12\, ps$

# Something new: X(3872)

- **Observed by Belle, confirmed by TeV, but what is it?**
  - Charmonium?
  - DD "molecule"?
- **Seen in $X \rightarrow J/\psi\pi\pi$ at TeV**
  - $\psi(2S) \rightarrow J/\psi\pi\pi$ is reference channel

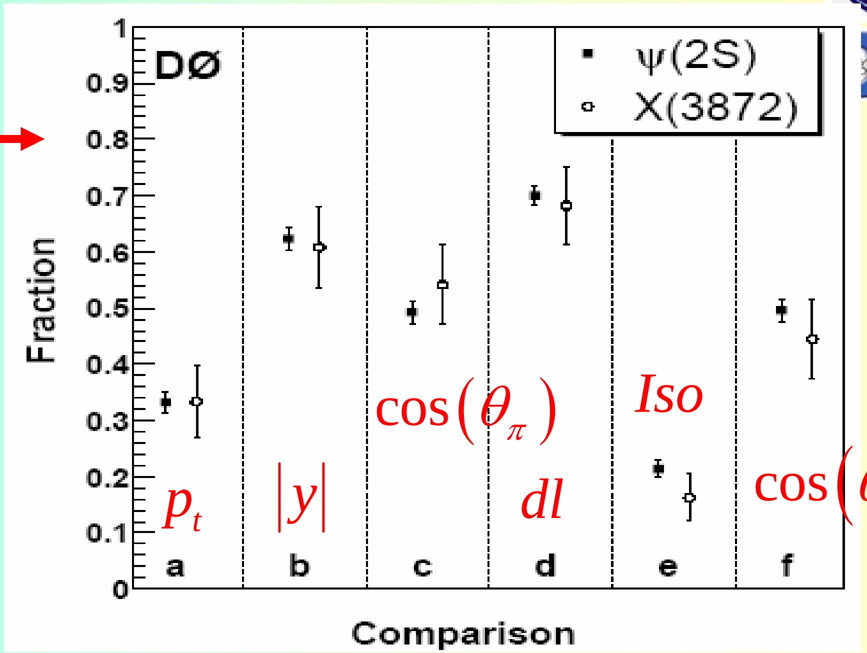



| X | CDF | DØ |
|---|---|---|
| Mass [GeV/$c^2$] | 3871.3±0.7±0.4 | 3871.8±3.1±3.0 † |

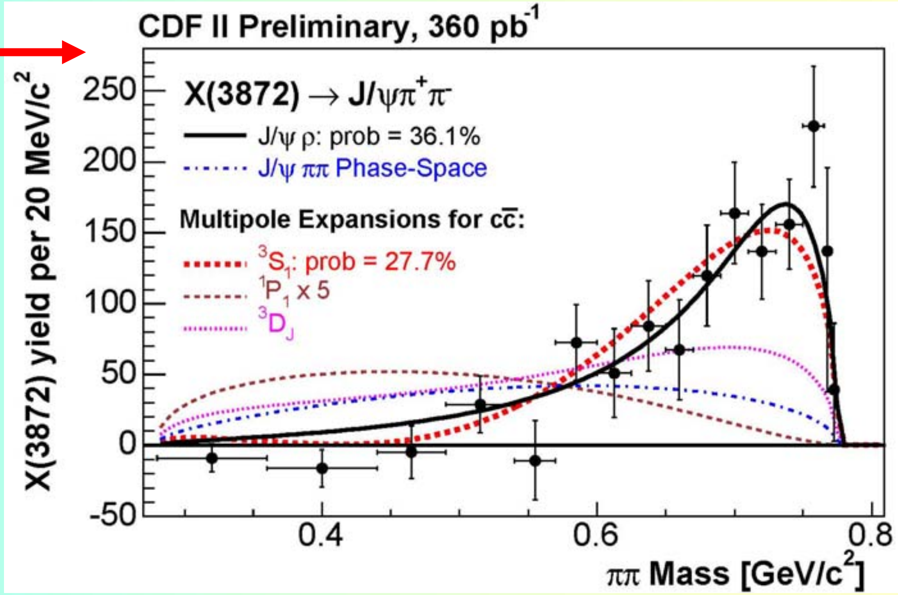
*† Addition of m(J/ψ) by SN*

# Further X Studies

- **DØ: Measure fractional production versus kinematic quantities**
  - Compare with ψ(2S)
  - "Charmonium"-like




- **CDF: Examine the $m_{\pi\pi}$ spectrum versus theory**
  - Rules out some, but none perfect



# Other Heavy Flavor Production

- **B**(L=1) $\to B\pi$**
  - **$B \to J/\psi K$ and $D\pi$ modes**
  - **Important to understand impact for mixing**

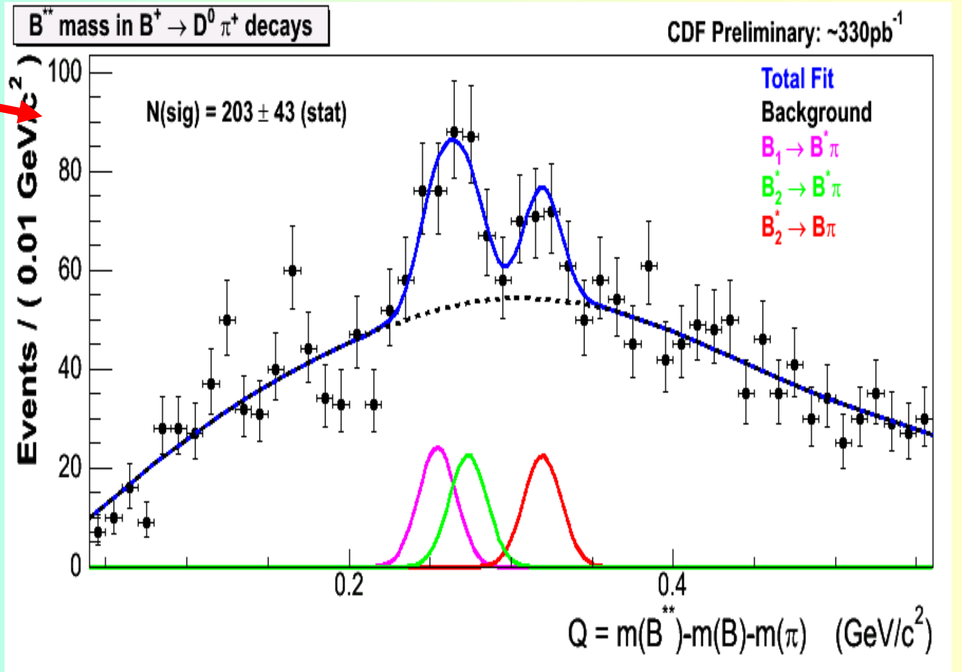
S Z8: CDF Pursley

- **Cross section $B \to \ell \nu D X$**
  - **Complement to $J/\psi$ mode**

S Z8: CDF Kraus

- **$J/\psi$ Spin Alignment**
  - **Test "Octet" Production model**

S Z8: CDF Kim




Common $\sigma$

$$m\left(B_2 \to B\pi\right) - m\left(B_2 \to B^*\pi\right) = 45\, MeV/c^2$$

$$f\left(B_2 \to B\pi\right) = f\left(B_2 \to B^*\pi\right)$$

**DØ**

$$m_{B_1} = 5274 \pm 4 \pm 7\, MeV/c^2$$

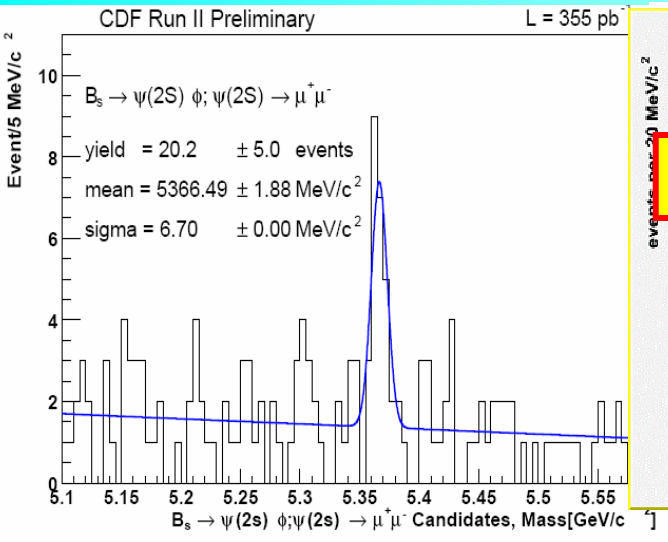
$$\Delta m\left(B_2^* - B_1\right) = 23.6 \pm 7.7 \pm 3.9\, MeV/c^2$$

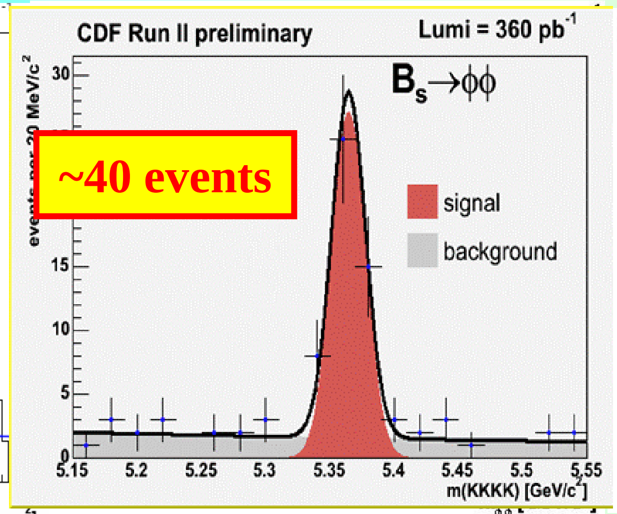
# Heavy Flavor Decays

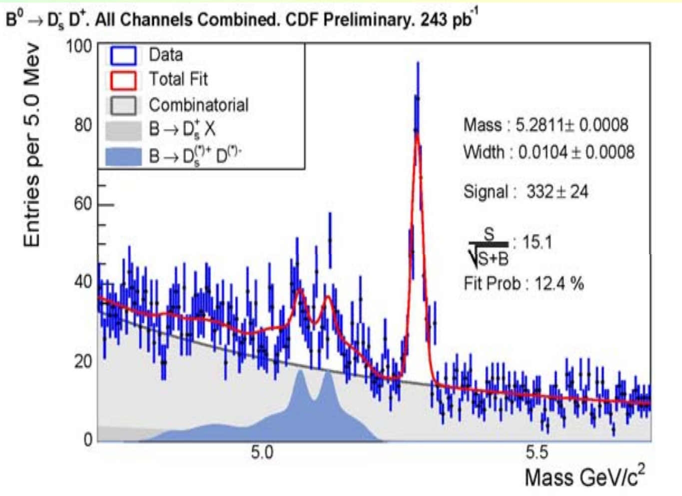
- New Modes
  - Test against theory predictions
  - Add statistics for mother particle studies
  - Help understand background in other analyses
- Rare decays limit contributions New Physics
- CP Violation in Decay
  - cf. Babar …

# Plethora of new channels

| S J8: CDF Kong | S Z8: CDF De Lorenzo | S Z8: CDF Iyutin |
| --- | --- | --- |
| • $B_s \to \psi(2S)\phi$ | • $B_s \to \phi\phi$ | • $B \to D_s D$ |
| $$\frac{Br\left(B_s \to \psi(2S)\phi\right)}{Br\left(B_s \to J/\psi\phi\right)} =$$ $$0.52 \pm 0.13 \pm 0.04 \pm 0.06(BR)$$ | $$\frac{Br\left(B_s \to \phi\phi\right)}{Br\left(B_s \to J/\psi\phi\right)} =$$ $$\left(10^{+5}_{-4} \pm 1\right) \times 10^{-3}$$ | $$\frac{Br\left(B^0 \to D^+ D_s\right)}{Br\left(B^0 \to D^+ \pi\pi\pi\right)} =$$ $$2.00 \pm 0.16(NC) \pm 0.12(sys) \pm 0.16(BR)$$ |



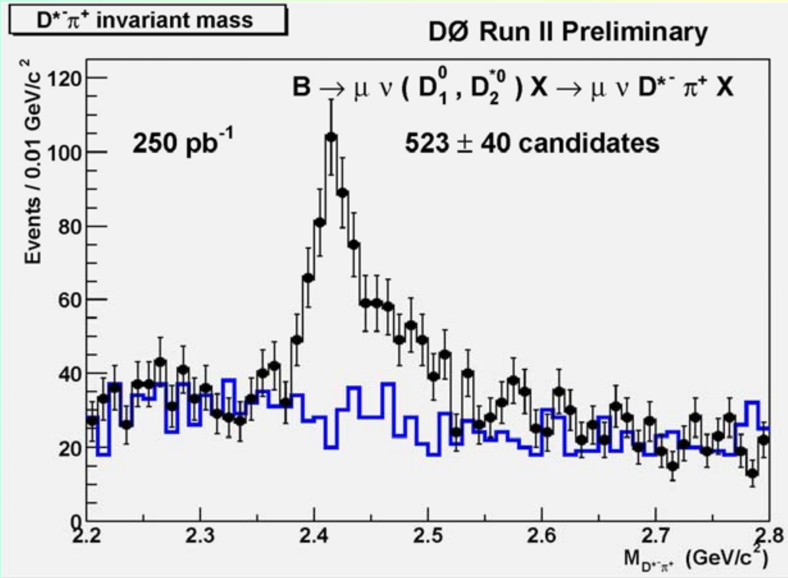



# Semileptonic decays to excited states

- **$B \to D^{**}\mu\nu$**

$$Br\left(B \to \mu\nu[D_1^0(2420), D_2^{*0}(2460)]X\right) \otimes$$
$$Br\left([D_1^0(2420), D_2^{*0}(2460)] \to D^{*+}\pi^-\right)$$
$$= \left(0.280 \pm 0.021 \pm 0.088\right)\%$$

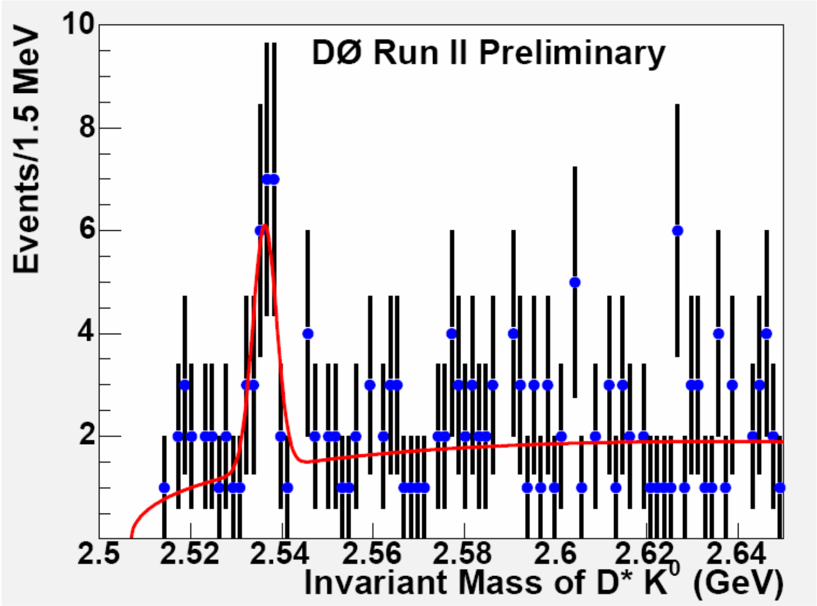
S Z8: DØ Tsybychev




- **$B_s \to D_s^{**}\mu\nu$**
  - **$D_s^{**} \to D^*K_S$**

$$\text{Excess: } 20.6 \pm 5.6 \left(3.7\sigma\right)$$

S C8: DØ Rieger

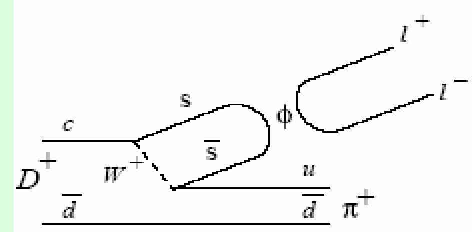


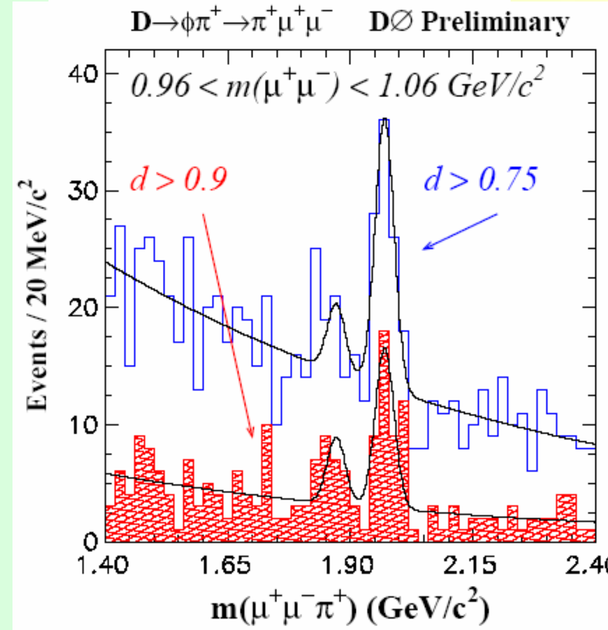
# Rare Decays

- **FCNC Charm Decays $c \to u\mu\mu$**
  - $D \to \phi\pi \to \mu\mu\pi$ **relative to $D_s$**
  - **Precusor to nonresonant study**

$$Br\left(D^{\pm} \to \phi\pi^{\pm} \to \mu^{+}\mu^{-}\pi^{\pm}\right) < 3.1\times10^{-6}\ @90\%$$

S J9: DØ Casey

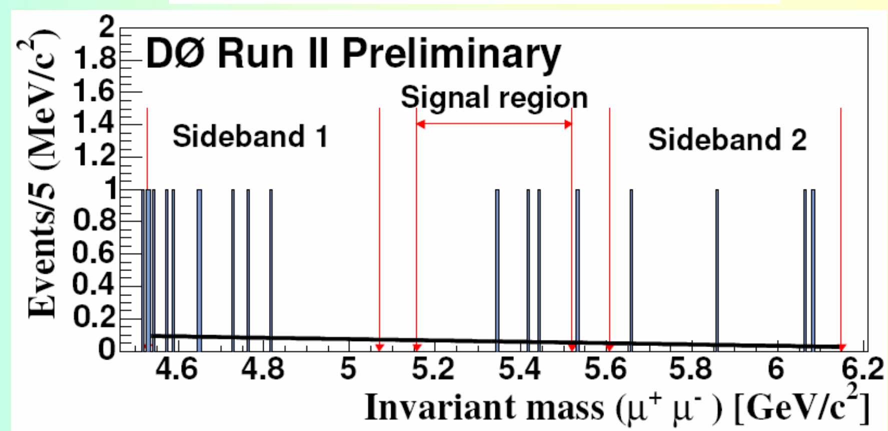



- **$B_s \to \mu\mu$ $\mathcal{B}r_{SM} \sim 10^{-10}$ New Physics!**
  - **4.3 ±1.2 expected, 4 seen**

$$Br\left(B_s \to \mu^{+}\mu^{-}\right) < 3.7\times10^{-7}\ @95\%$$

**CDF** $$Br\left(B_s \to \mu^{+}\mu^{-}\right) < 2.0\times10^{-7}\ @95\%$$



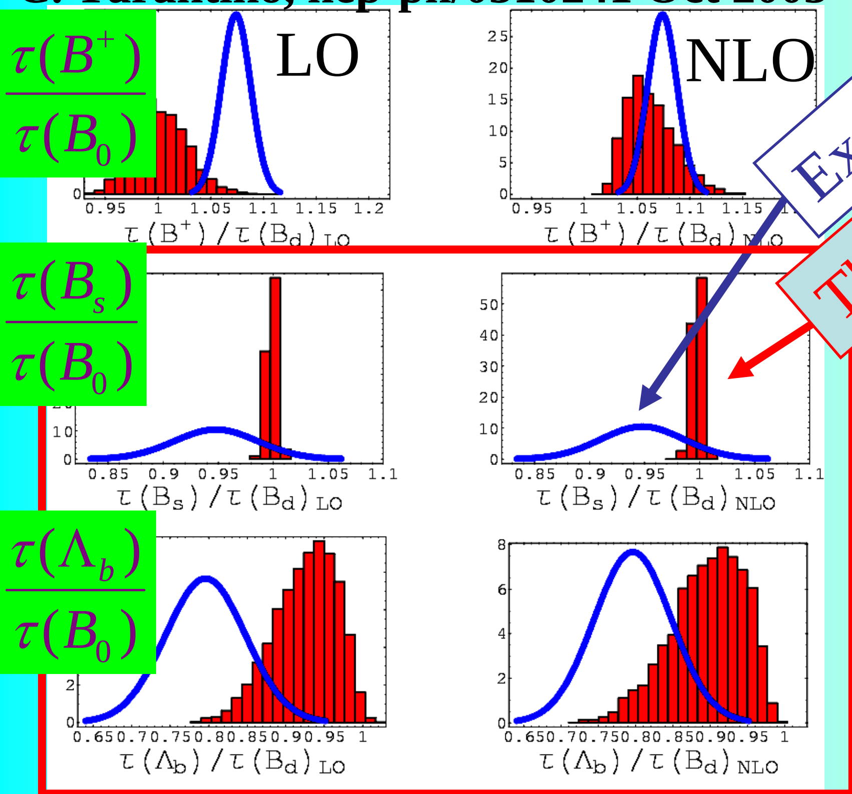

- **$B_s \to \mu\mu\phi$**
  - **Sensitivity:** $$\frac{\langle Br(B_s \to \mu\mu\phi)\rangle}{Br(B_s \to J/\psi\phi)} = 0.013$$

S J8: DØ Bernhard

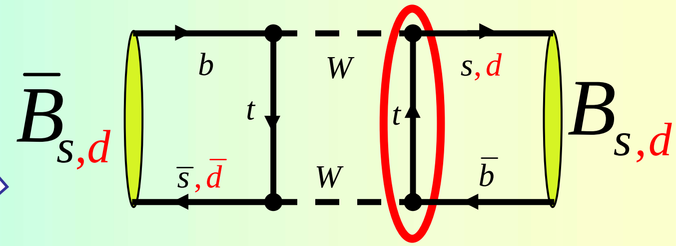
# Lifetimes and Mixing

- **Prereq to Mixing**
- **Test HQE theory**

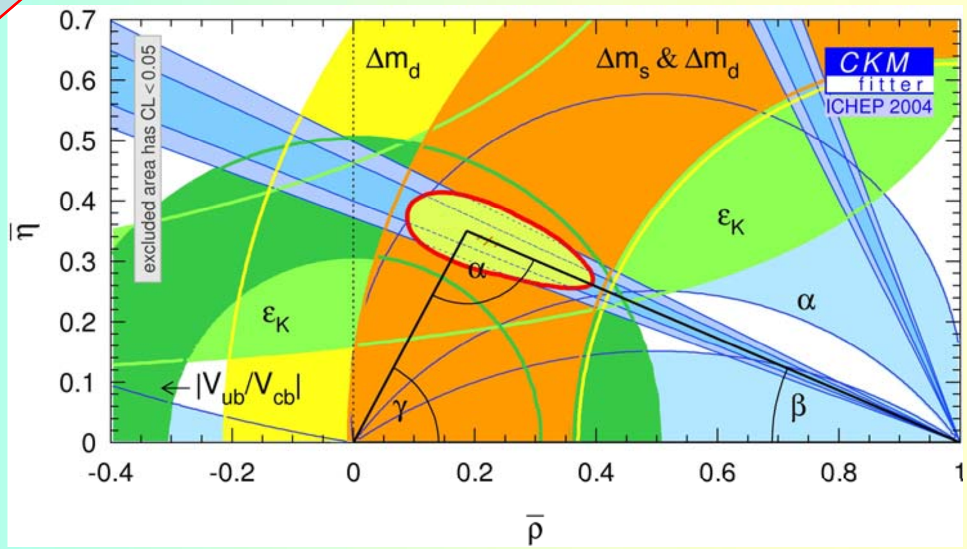
**C. Tarantino, hep-ph/0310241 Oct 2003**




- **B mixing → CKM**




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



# Heavy Flavor Lifetimes

S Z8: CDF Miles Clark

S U12: CDF Da Ronco

S J8: DØ Casey

- **Tevatron Industry**
  - Typically Simultaneous Mass and Lifetime fit

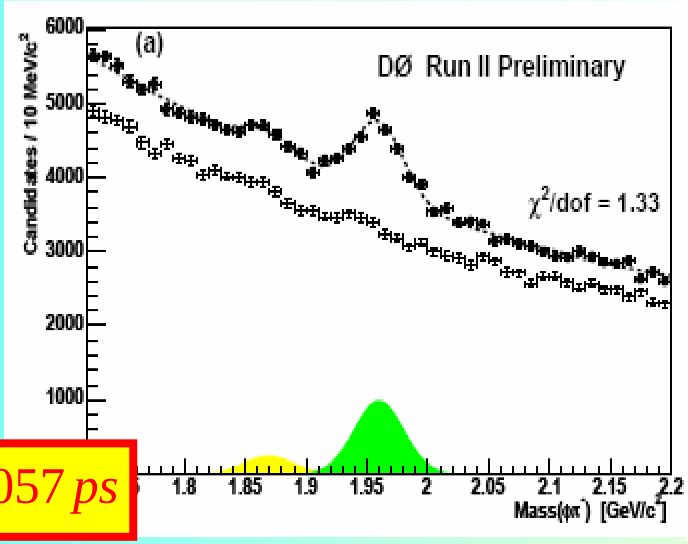
| | Mode | CDF [ps] | DØ [ps] | HFAG 04 |
|---|---|---|---|---|
| $\tau(B^+)$ | $J/\psi$ | 1.662±0.033±0.008 | | 1.653±0.014 |
| | $l\upsilon$ | 1.653±0.029 ±0.032 | | |
| | hadrons | 1.66±0.03±0.01 | | |
| $\tau(B^0)$ | $J/\psi$ | 1.539±0.051±0.008 | 1.473±0.051±0.023 | 1.534±0.014 |
| | $l\upsilon$ | 1.473±0.036±0.054 | 1.547±0.023±0.020±0.017† | |
| | hadrons | 1.51±0.07±0.01 | | |
| $\tau(B_s)$ | $J/\psi$ | 1.369±0.100±0.009 | 1.444±0.094 ±0.020 | 1.469±0.059 |
| | $l\upsilon$ | | 1.420±0.043 ±0.057 | |
| | hadrons | 1.60±0.10±0.02 | | |
| $\tau(\Lambda_b)$ | $J/\psi$ | 1.25±0.26±0.10 | 1.22+0.22-0.18 ±0.04 | 1.232±0.072 |

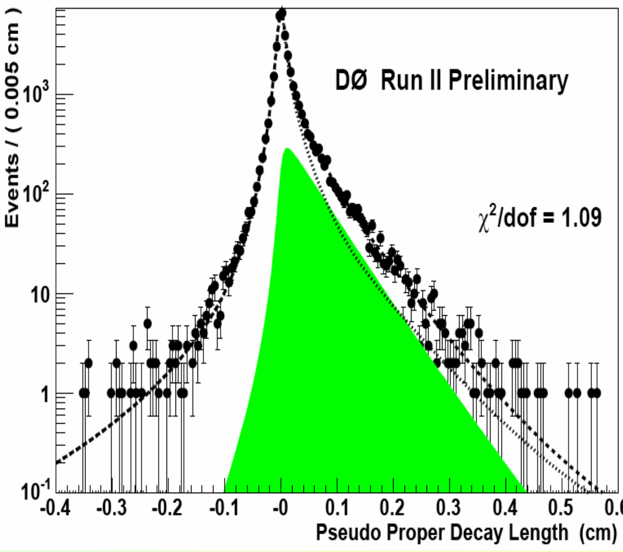
† From $\tau_+/\tau_0 \oplus \tau_+^{PDG04}$ by SN

# Example Lifetimes: $B_s$

- **DØ $B_s \to D_s \ell \upsilon$**
  - $D_s \to \phi\pi$
  - Overcome $\upsilon$ w/simulation

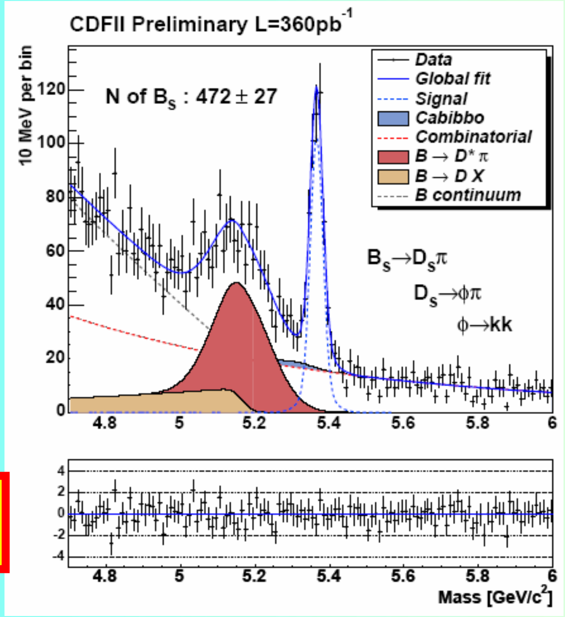
$$\tau\left(B_s\right) = 1.420 \pm 0.043 \pm 0.057\, ps$$

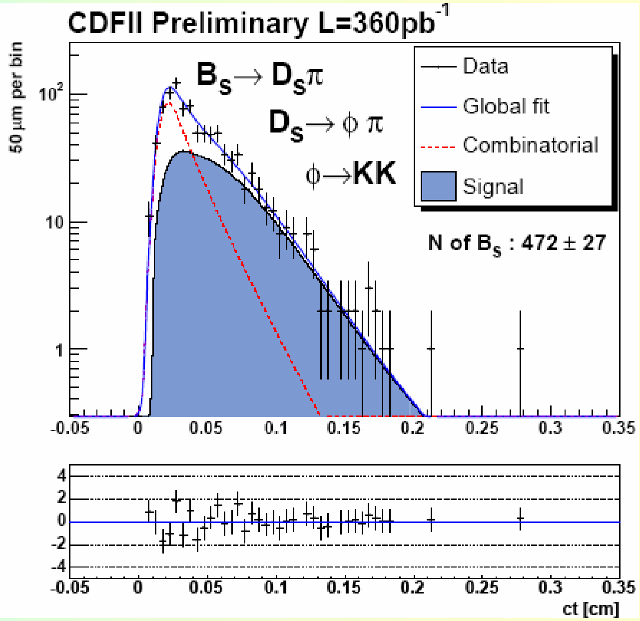



- **CDF $B_s \to D_s\pi$**
  - $D_s \to \phi\pi$
  - Trigger Bias

$$\tau\left(B_s\right) = 1.60 \pm 0.10 \pm 0.02\, ps$$



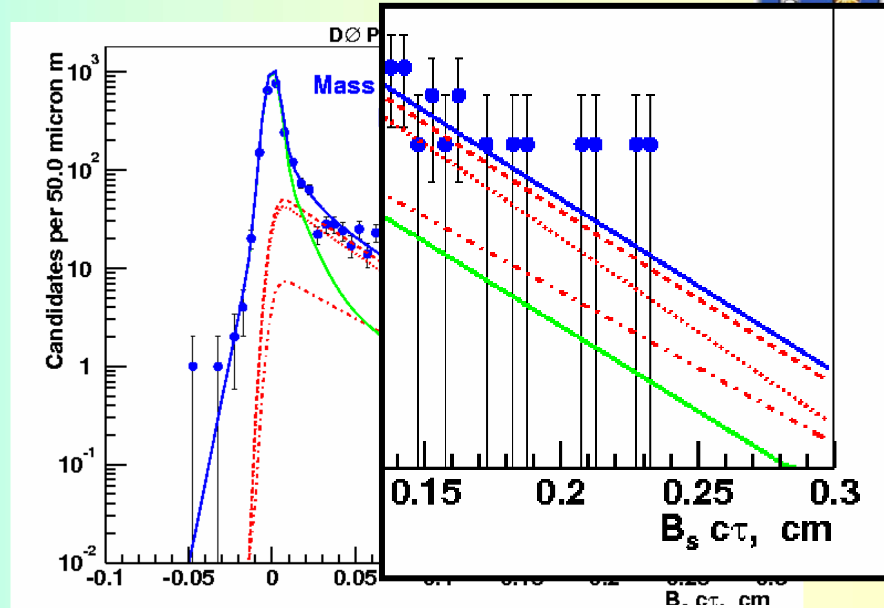
# $B_s$ Lifetime Difference $\Delta\Gamma$

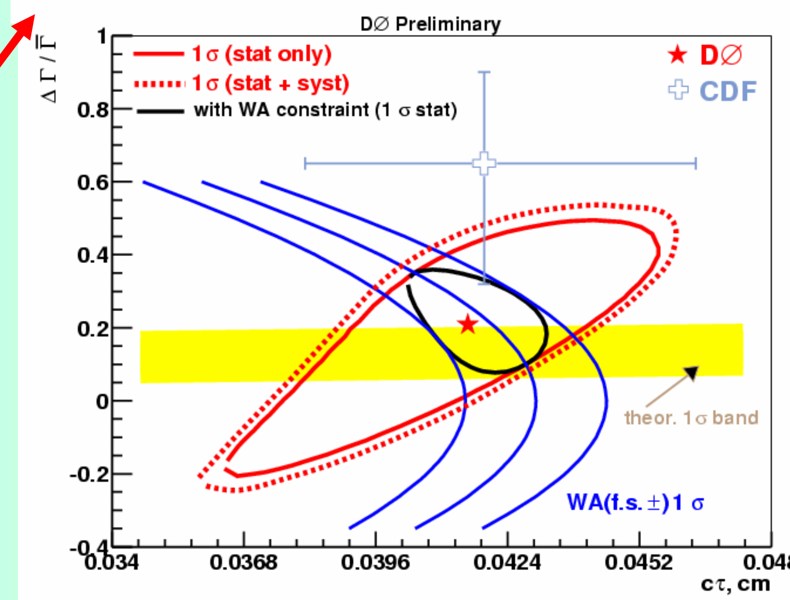
S H8: DØ Welty

- $B_s \to J/\psi\phi$
  - $B \to$VV, mixture of CP even/odd separate by angular analysis
  - Combine two-lifetime fit + angular$\to$ $\Delta\Gamma_s=\Gamma_H-\Gamma_L$
  - SM $\Delta\Gamma_s/\Gamma_s=0.12\pm0.06$ (Dunietz, Fleischer & Nierste)
- Indirect Measurement of $\Delta m_s$
  - $\left.\dfrac{\Delta\Gamma_s}{\Delta m_s}\right|_{SM} = \left(3.7^{+0.8}_{-1.5}\right)\times 10^{-3}$

$$\frac{\Delta\Gamma}{\Gamma}\left(\text{DØ } 450\ pb^{-1}\right) = 0.21\,^{+0.33}_{-0.45}$$

$$\frac{\Delta\Gamma}{\Gamma}\left(\text{CDF } 240\ pb^{-1}\right) = 0.65^{+0.25}_{-0.33}\pm 0.01$$



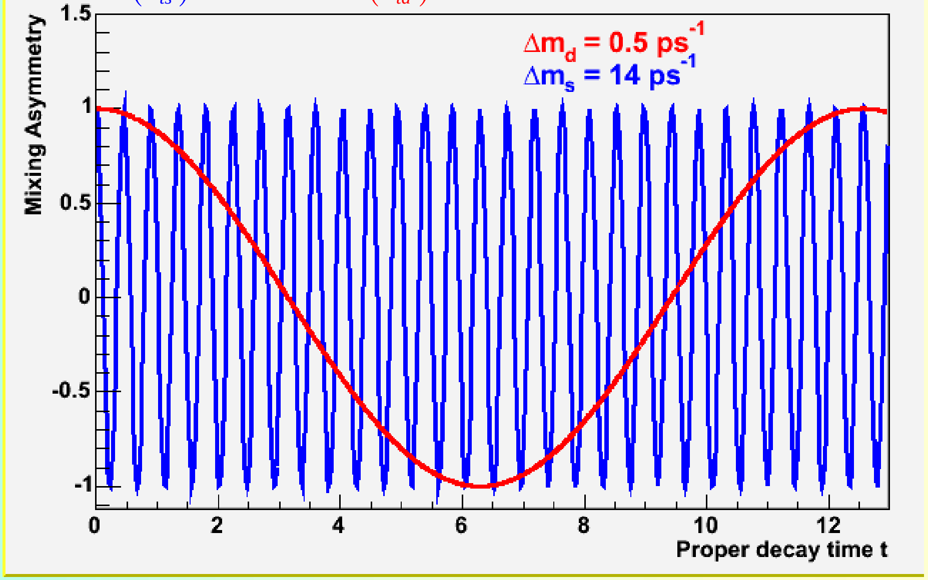



# Direct B mixing in a nutshell

- **Measure Asymmetry**
- **Determine "time" of Decay: $\sigma_t$ = Proper lifetime resolution**
  - **measure decay length, apply boost**
- **Sort the mixed from unmixed via b charge at production and decay**
  - ***$S \times \varepsilon$* = Signal Yield × efficiency for making a determination**
  - ***D* = "Dilution" = (2P-1); P = Probability of correct assignment**

$$\mathcal{A}_{\text{mix}}(t) = \frac{N_{\text{mix}}(t) - N_{\text{unmix}}(t)}{N_{\text{mix}}(t) + N_{\text{unmix}}(t)} \propto \cos \Delta m t$$

$\mathrm{Re}(V_{ts}) \approx 0.040 > \mathrm{Re}(V_{td}) \approx 0.007$




$$\mathrm{Sig}(\Delta m) = \sqrt{\frac{S}{S+B}}\, e^{-(\Delta m \sigma_t)^2/2} \sqrt{\frac{S \varepsilon D^2}{2}}$$

# Calibration on $B_d$

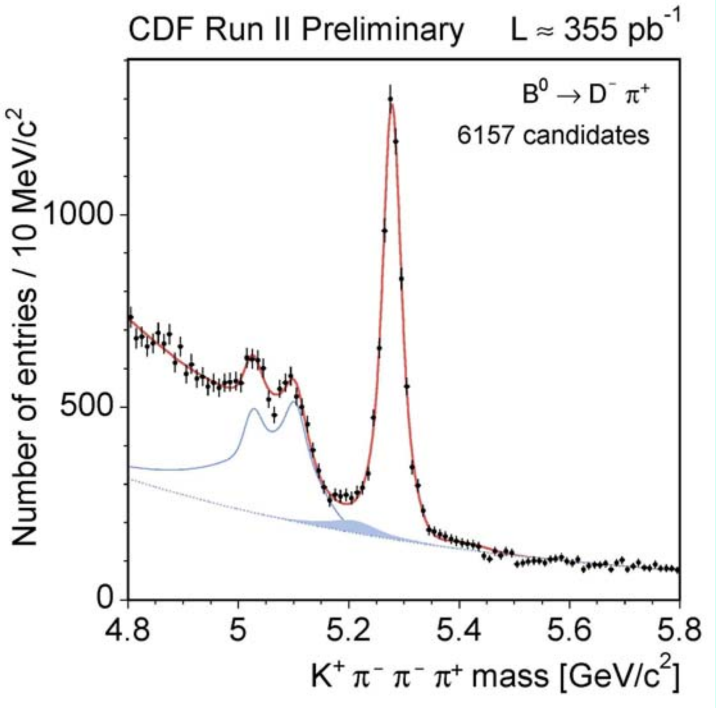
S H8: CDF Giurgiu and Belloni
U 12: DØ Naimuddin and Krop

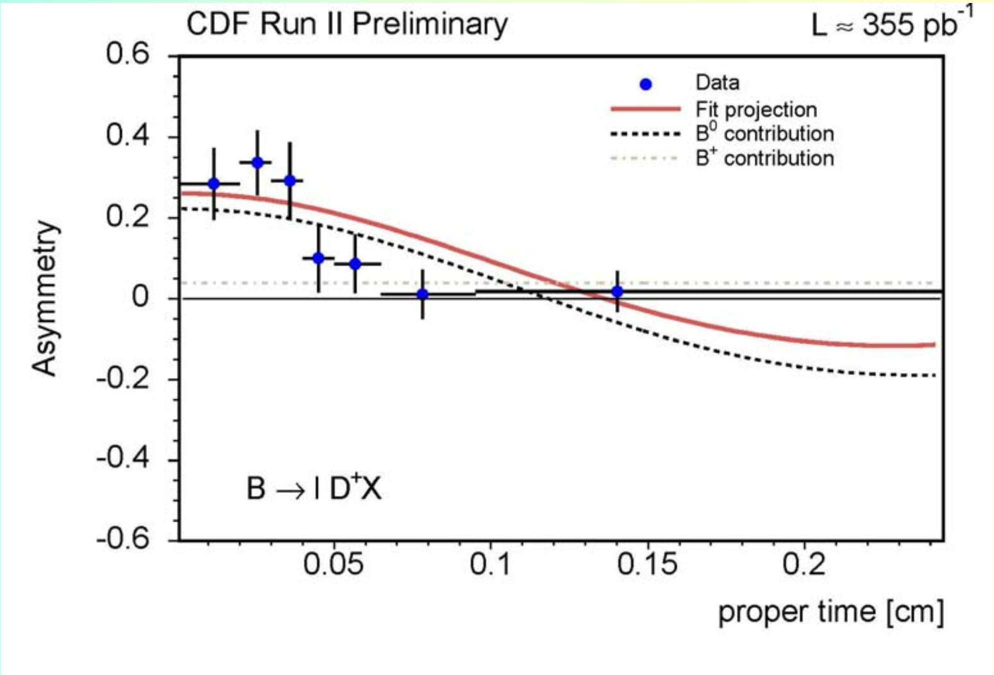
- **Know the right answer**
  - **Tests Fitting Mechanism**
  - **Calibrates Tagging**
  - **Much higher statistics**

*CDF*
$$\Delta m_d = 0.503 \pm 0.063 \pm 0.015\, ps^{-1}$$
$$\varepsilon D^2 = 1.12 \pm 0.18 \pm 0.04\%$$

*DØ*
$$\Delta m_d = 0.558 \pm 0.048\, ps^{-1}$$
$$\varepsilon D^2 = 1.16 \pm 0.16$$

$\Delta m_d = 0.510 \pm 0.006\, ps^{-1}$ (HFAG Winter 05)



# $B_s$ Mixing Results

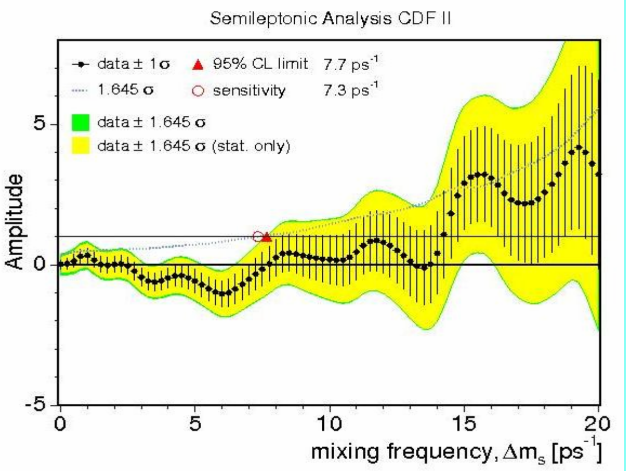
S J8: CDF Giurgiu
U 12: DØ Naimuddin/Krop

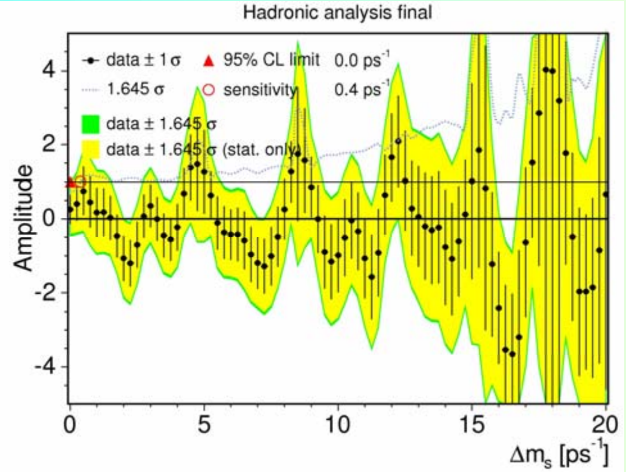
- **Amplitude Scan**
  - **Fourier Transform into $\Delta m$ space only floating $A$**

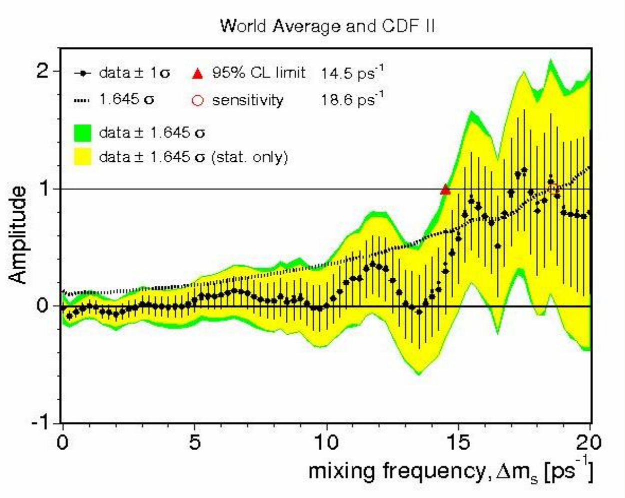
$$\mathcal{L}_t \propto \left(1 + A \cdot D \cos\left(\Delta m t\right)\right)$$

  - **$A$ = 1 for true Δm, 0 else**
  - **Limit ≡ $A + 1.645\sigma_A = 1$**
  - **Sensitivity ≡ $1.645\sigma_A = 1$**
  - **NIM A384(1997) p.491 ff.**

| Source | $\Delta m_s >$ (95%) | Sensitivity |
|---|---|---|
| DØ $D_s l\nu$ | 5.0 ps$^{-1}$ | 4.6 ps$^{-1}$ |
| CDF $D_s l\nu$ | 7.7 ps$^{-1}$ | 7.3 ps$^{-1}$ |
| CDF $D_s\pi$ | 0.0 ps$^{-1}$ | 0.4 ps$^{-1}$ |
| CDF Comb. | 7.9 ps$^{-1}$ | 8.4 ps$^{-1}$ |
| PDG 04 | 14.5 ps$^{-1}$ | 18.1 ps$^{-1}$ |
| PDG 04⊕CDF | 14.5 ps$^{-1}$ | 18.6 ps$^{-1}$ |



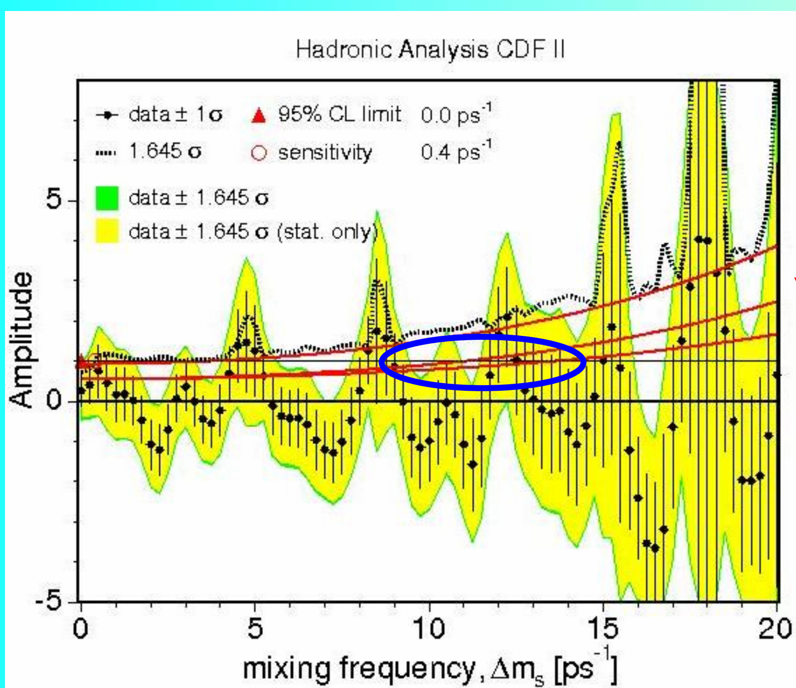



# Potential in $B_s$ Mixing

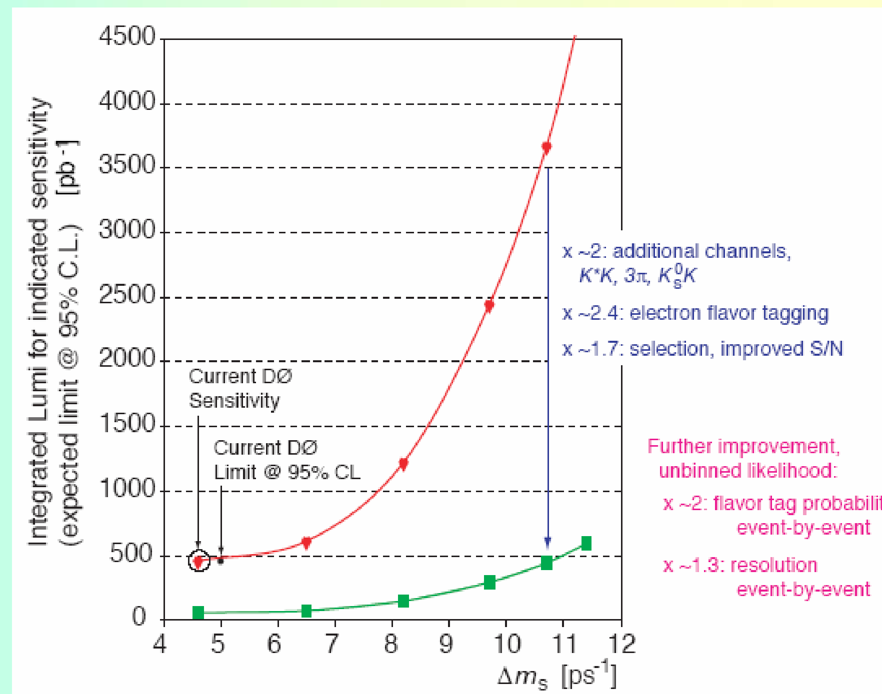
S U12: "Tevatron techniques in B Physics" CDF and DØ

- **Statistics: *If* gain factor of 4 from**
  - Opposite and Same Side Kaon Tagging (CDF), Electron Tagging (DØ)
  - More Channels, More Luminosity, Smarter Triggers
  - Multivariate Tagging approach
- **And *If* gain 20% on Proper Time resolution**
  - Event By Event Primary Vertexing
  - Better $\sigma_t$ understanding




+20% Resolution

4 × Statistics



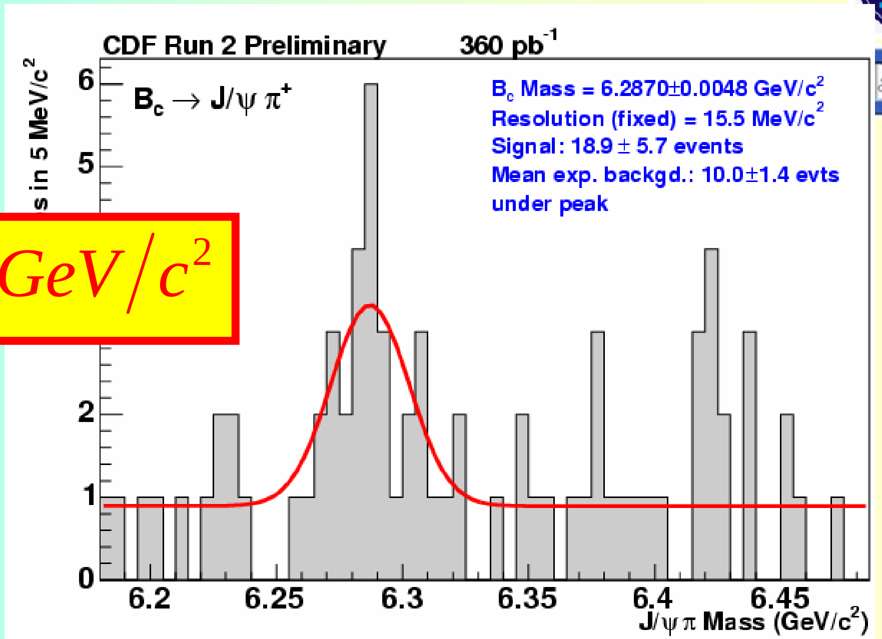
# Whew!

- **Tremendous amount of Heavy Flavor activity going on at the Tevatron**
  - **Squeezing Physics from data samples available nowhere else**
  - **Manpower limited**
- **Most of the Luminosity still to come**
  - **We're at 0.8, expect >4 $fb^{-1}$ total**
  - **Crucial "Run 2b" upgrades done this fall**
    - **CDF: Track Trigger, Displaced Vertex Trigger …**
    - **DØ: Inner Silicon Layer, Track Trigger …**

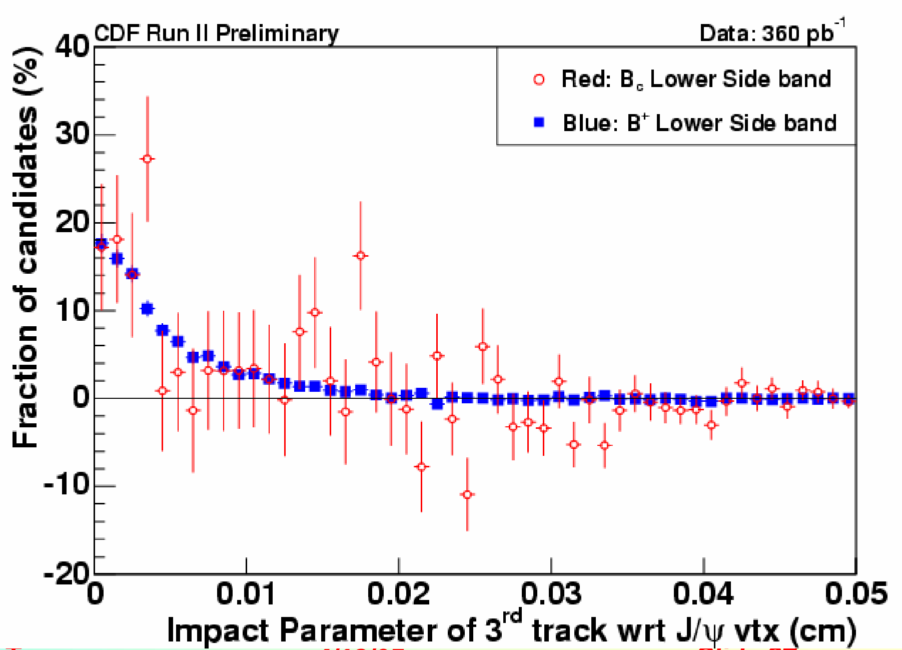
# Backup Slides

# $B_c \rightarrow J/\psi\, \pi$

$$m_{B_c} = 6.2870 \pm 0.0048 \pm 0.0011\, GeV/c^2$$




- **Fully reconstructed**
  - Good mass resolution
- **Is it significant?**
  - Analysis done "blind"
  - Loosen cuts, look for partial reconstructed $B_c$ in low mass sideband
    - compare $d_0(\pi)$ w.r.t. $J/\psi$
  - See similar excess in $B^+$

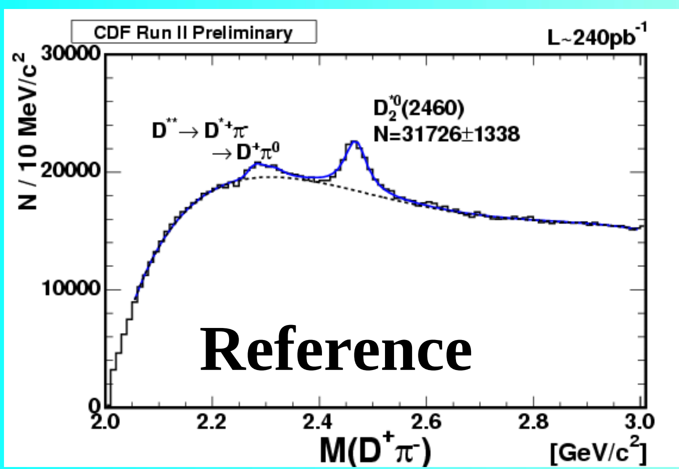


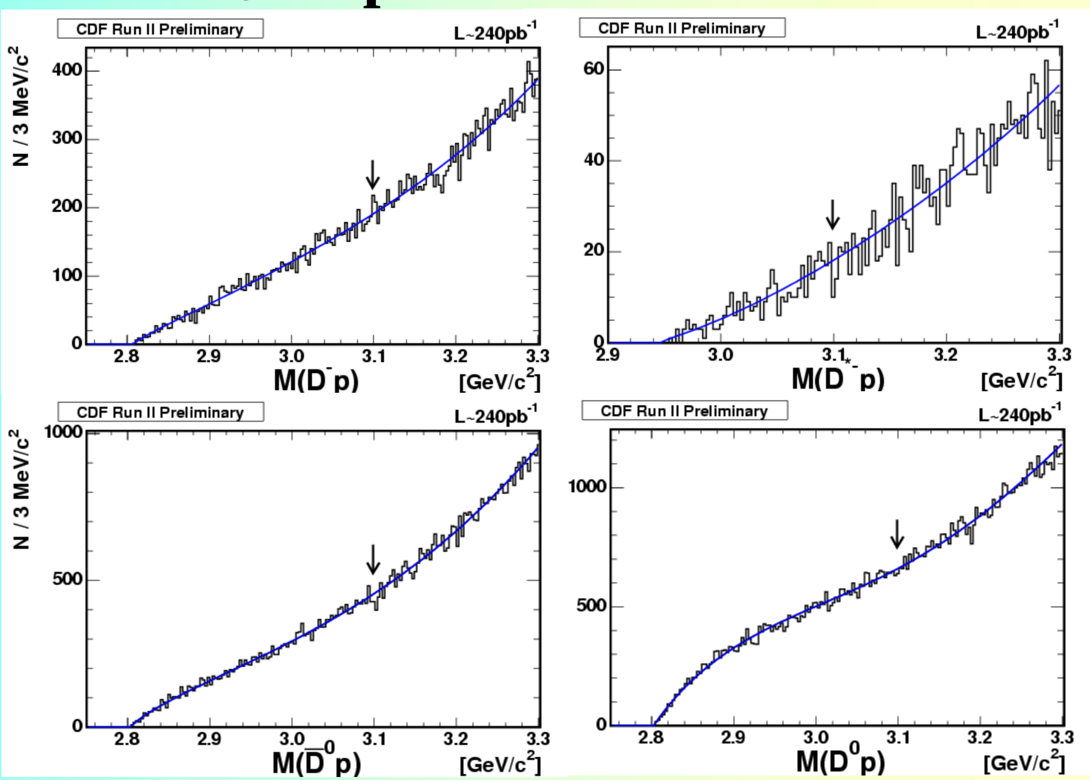
S Y12: CDF Field

# Pentaquark Production?

- [5 quark bound state] → Baryon-Meson
- Observed elsewhere: Can they be seen at TeV?
  - same trigger/kinematic range as Heavy Flavor
  - many reference decays

$\theta_c \to Dp \quad m \approx 3.1\ GeV/c^2$




# None Seen

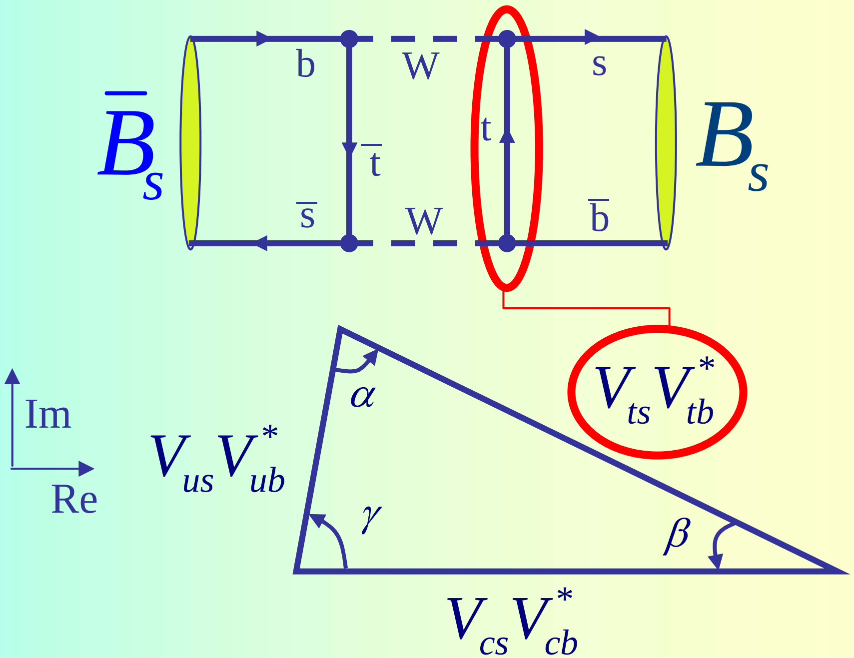
# Standard Model Mixing

- **In Standard Model, Mixing from CKM matrix**
  - **Flavor states not mass eigenstates on the quark level**
  - **CP Violation inherent with ≥3 generations**
- **Comes in through loops, akin to New Physics**
  - **Mixing sensitive to other particles in loop**

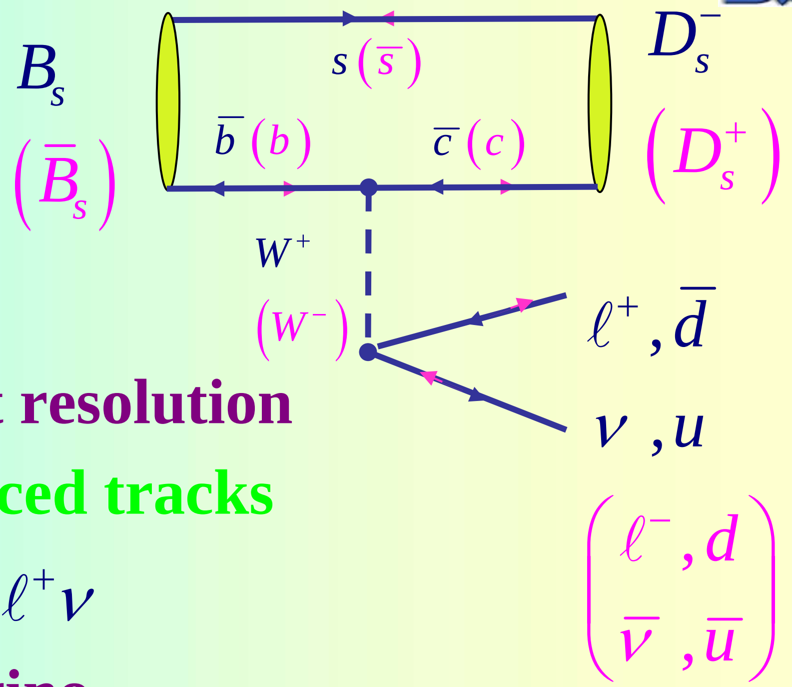
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

$$CPT : V^{\dagger}V = 1$$

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



# Mixing Channels of interest




- **Decay chain tags the flavor**
  - **Lepton/Pion from b decay**
- **Hadronic Decays** $B_s \to D_s^- \pi^+$
  - **Fully reconstructed $\Rightarrow$ excellent resolution**
  - **Trigger on pair of 2 GeV displaced tracks**
- **Semi-leptonic decays** $B_s \to D_s^- \ell^+ \nu$
  - **Higher statistics, but miss neutrino**
  - **Trigger on 2 GeV displaced track and 4 GeV lepton**
- **Collect multiple $D_s$ decays**

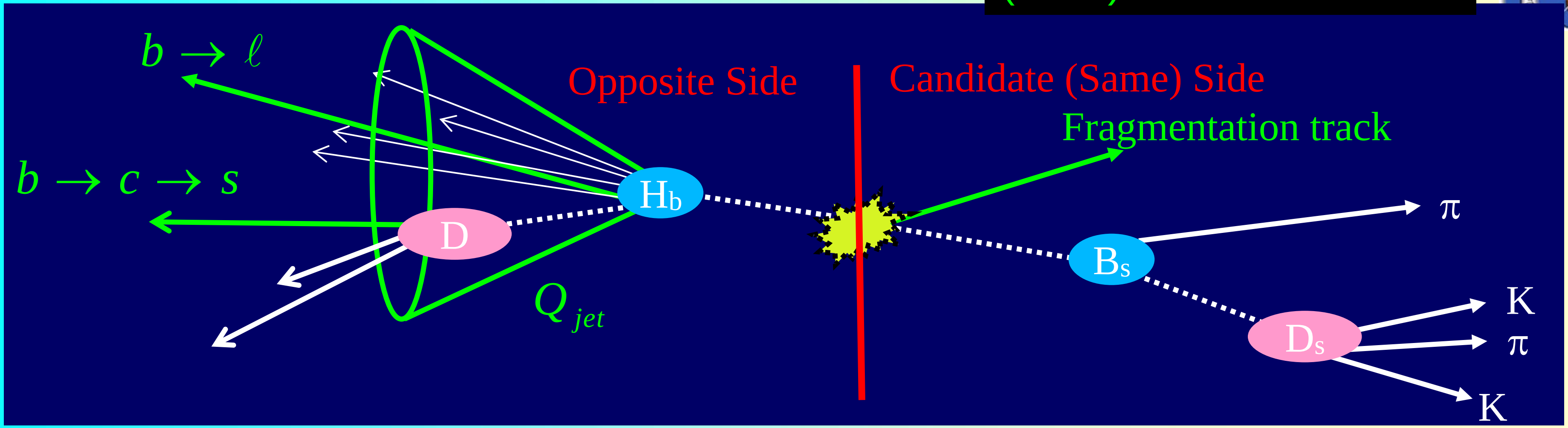
$$D_s^\pm \to \phi\pi^\pm; \phi \to K^+K^-$$

$$D_s^\pm \to K^*K^\pm; K^* \to K\pi$$

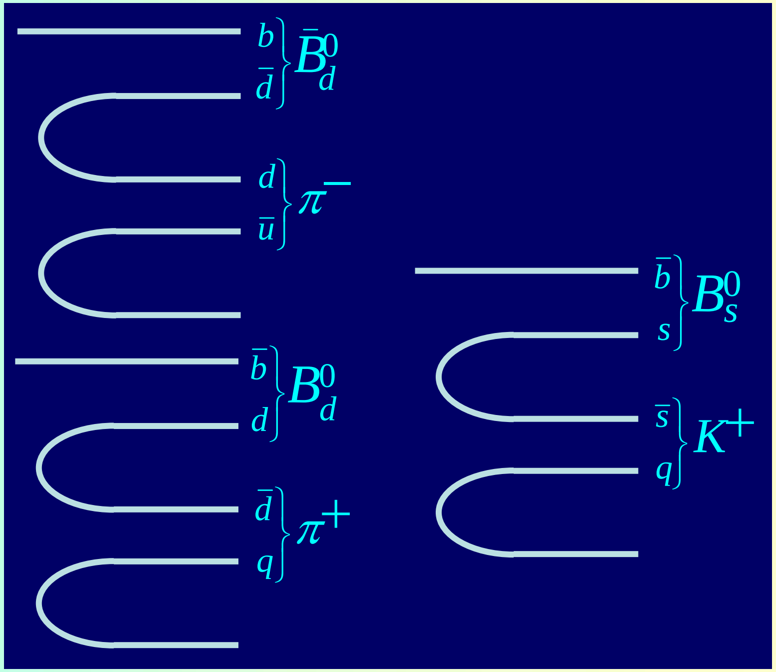
$$D_s^\pm \to \pi^+\pi^-\pi^\pm$$

# Production Flavor

S U12: "Tevatron techniques in B Physics" (Now!) CDF and DØ

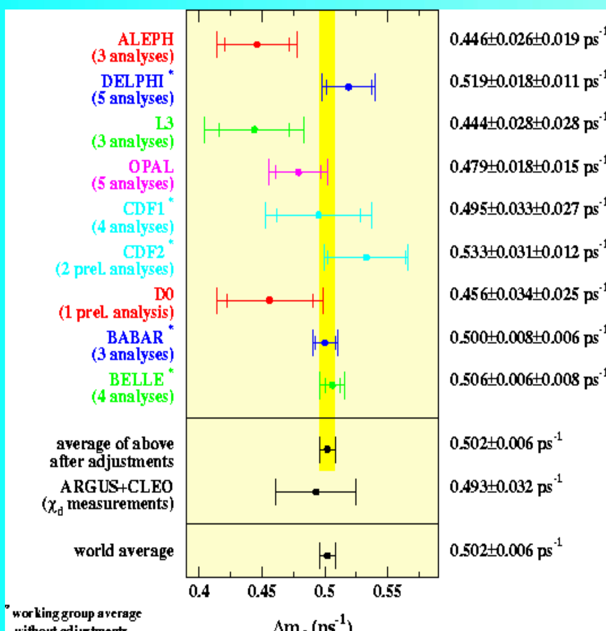


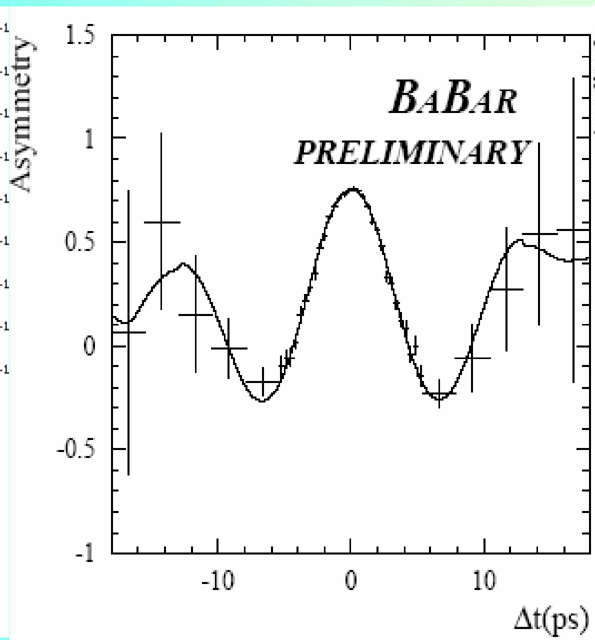

- **Look at associated particles**
  - **Other b decay**
    - **Lepton Charge**
    - **Charge of B decay products:**
    - **Kaon Charge**
  - **Nearest charged track**
    - **Vacuum gives net charge 0**

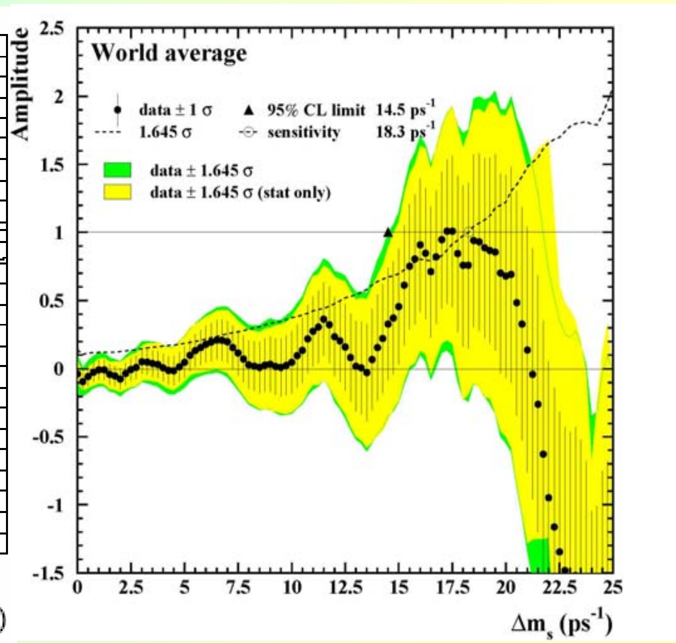


# Current World Knowledge

- $\Delta m_d$ **dominated by "B factories"** $e^+e^- \to \Upsilon(4S) \to B_{u,d}\bar{B}_{u,d}$
  - **Designed specifically for this purpose**
- $\Delta m_s$ **not accessible at B factories, have world ave.**
  - **Limit from** $e^+e^- \to Z \to b\bar{b}$ **and** $p\bar{p} \to b\bar{b}X$



# Measuring a limit: Amplitude Scan

- $\Delta m_s$ measurement is "blinded"
  - Study all systematics, sensitivity without looking at the answer
- Looks like a limit ⇒ Amplitude Scan
  - Fix tagging parameters from from $\Delta m_d$ measurement
  - Add Amplitude factor to the oscillation term, scan $\Delta m_s$ space
    - NIM A384(1997) p.491-505
- Check for $\Delta m_d$ :