# CDF's Charm and B Physics

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- B meson lifetimes
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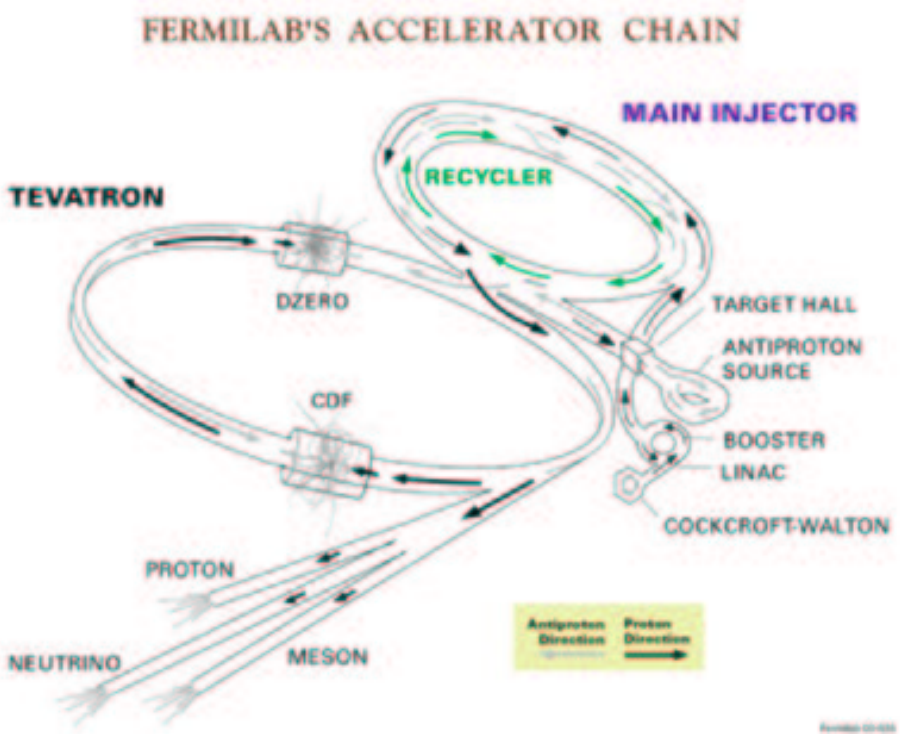
# Tevatron Upgrade

## Main Injector

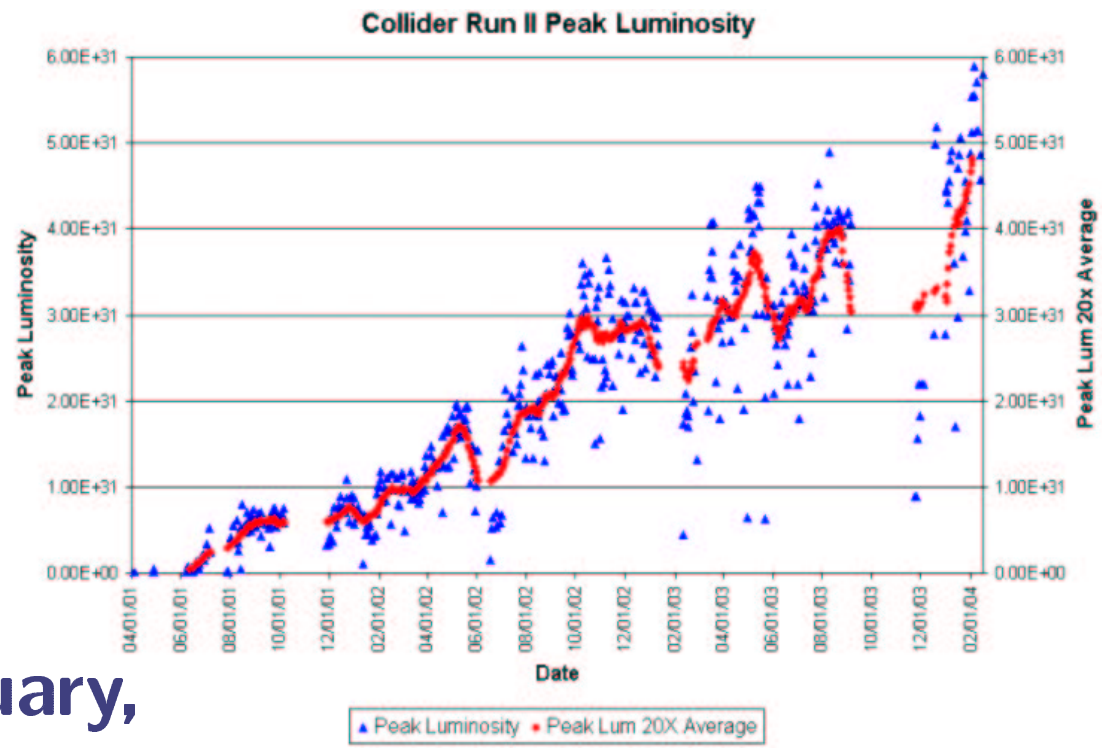
- New injection stage for Tevatron
- Ability to accelerate and deliver higher intensity of protons
- More efficient $\overline{\mathrm{p}}$ transfer
- $\overline{\mathrm{p}}$ recycler (**new**)




- Higher Collision rate: 396ns (36x36 bunches)
  $\Rightarrow$ **5-10 Higher Luminosity than run 1**
- Higher C.M. Energy: $1.8 \Rightarrow 1.96$ TeV

# Luminosity

## Tevatron Performance

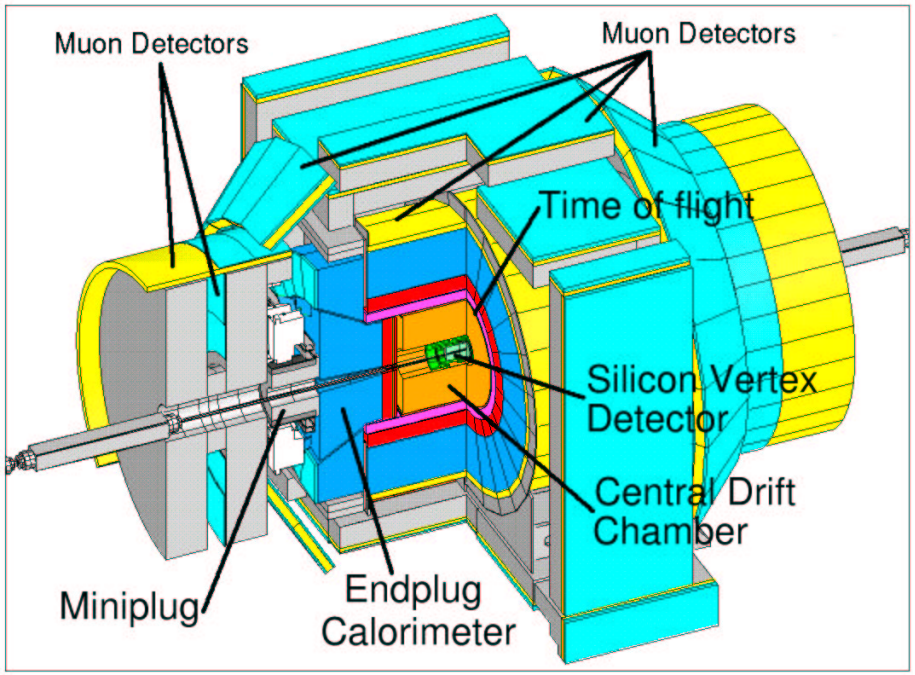



- typical luminosity: $4.5 \cdot 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
- record luminosity: $6.1 \cdot 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
  - at the end of January, $370\ \mathrm{pb}^{-1}$ delivered, $290\ \mathrm{pb}^{-1}$ recorded
  - efficiency in the high $80\%$'s, dead time $< 5\%$
  - analyses use different amounts of luminosity, mostly depending on when they were performed.

# The CDF II Detector

**Inherited from Run I:**

- **Central Calor. ($|\eta| < 1$)**
- **Solenoid (1.4 T)**




**Partially new:**

- **Muon System (extended to $|\eta| < 2$)**

**Completely new:**

- **3D Silicon Tracker ($|\eta| < 2$)**
- **Faster Drift Chamber**
- **Plug and Forward Calorimeters, Time Of Flight**
- **Trigger System (trigger on displaced vertices)**

# Drift Chamber Aging

- apparent aging of the drift chamber observed
- clearly visible in all inner superlayers
- fixes are in the works
  - increase gas flow by factor 10
  - add CF4 to the gas
- fixes will take weeks to implement
- in the meantime, innermost 2 superlayers turned off, gain reduced in the middle three
- even in this configuration, the tracker is still as good as D0's

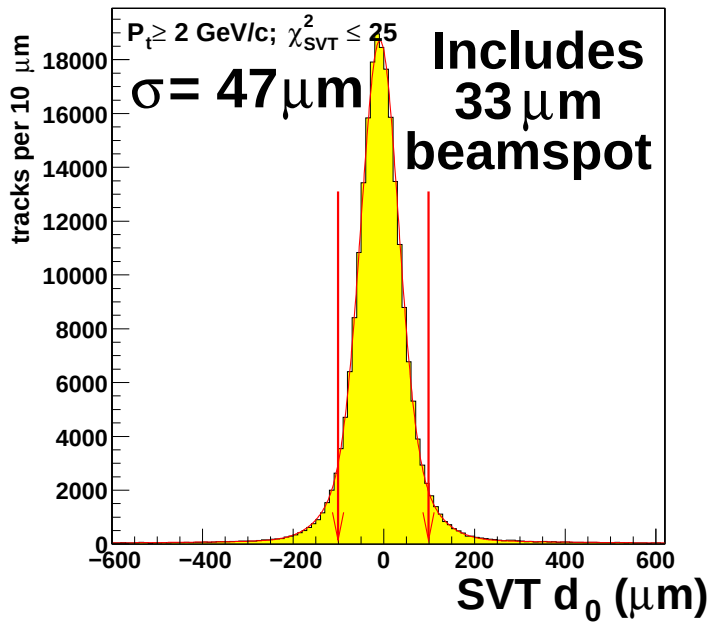
# Heavy Flavor Production

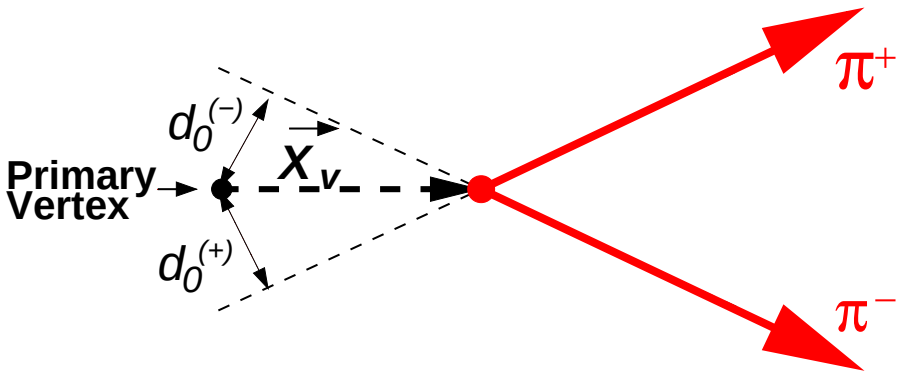
| Accelerator | PEPII/KEK($e^+e^-$) | Tevatron ($p\overline{p}$) |
|---|---|---|
| $\sigma(b\overline{b})$ | 1 nb | 100 $\mu$b |
| $\sigma(b\overline{b}) : \sigma(had)$ | 0.26 | 0.001 |
| Hadrons | $B^0, B^+$ | $B^0, B^+, B_s^0,$ $\Lambda_b, B_c^+ ...$ |
| Production | $\Upsilon(4S) \to B\overline{B}$ coherent | $b\overline{b}X$ incoherent |
| Environment | clean | messy |
| Boost | 0.5 | 2-4 |
| Event pile-up | no | yes |
| Trigger | inclusive | selective |
| Energy constraint | yes | no |

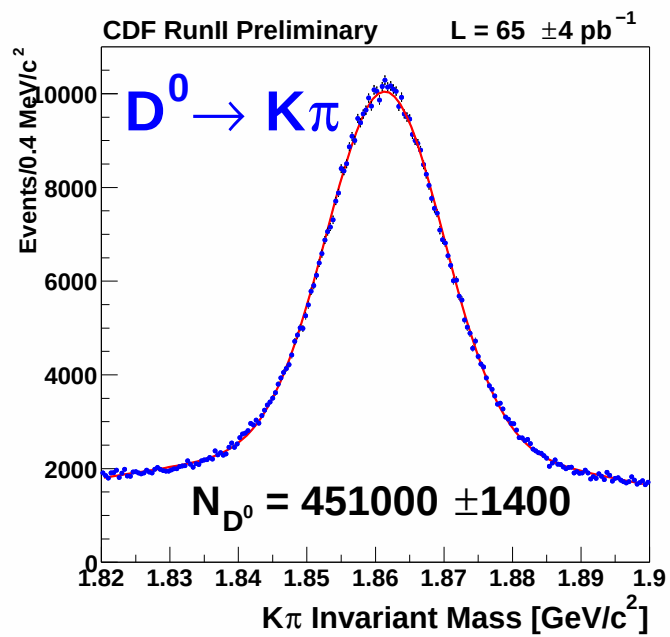
# CDF Run II B-triggers

- di-lepton triggers
- single lepton triggers
- new: displaced track triggers
- trigger $\mathrm{B} \to \pi\pi, \mathrm{B_s} \to \mathrm{D_s}\pi$
- trigger on 2 displaced tracks

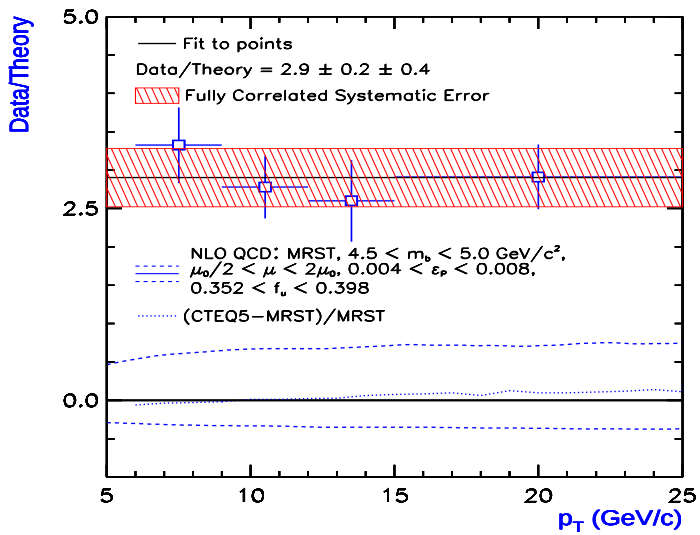
  $(\mathrm{p_T} > 2\ \mathrm{GeV}/c, 120\ \mu\mathrm{m} < |d_0| < 1\ \mathrm{mm})$
- challenge: read out SVX and track at 10's of kHz $\to$ SVT

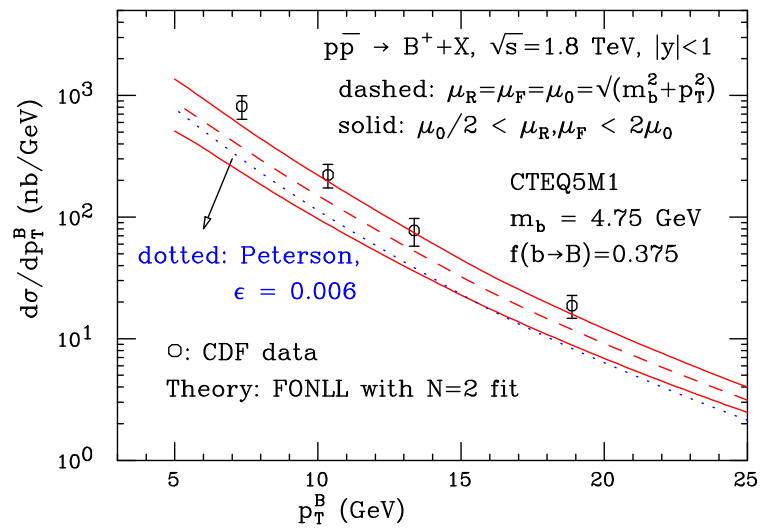


# Heavy Flavor Cross Section

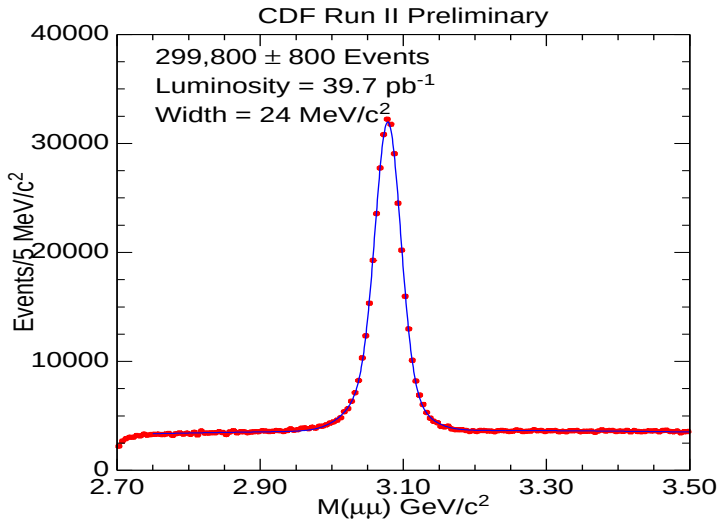


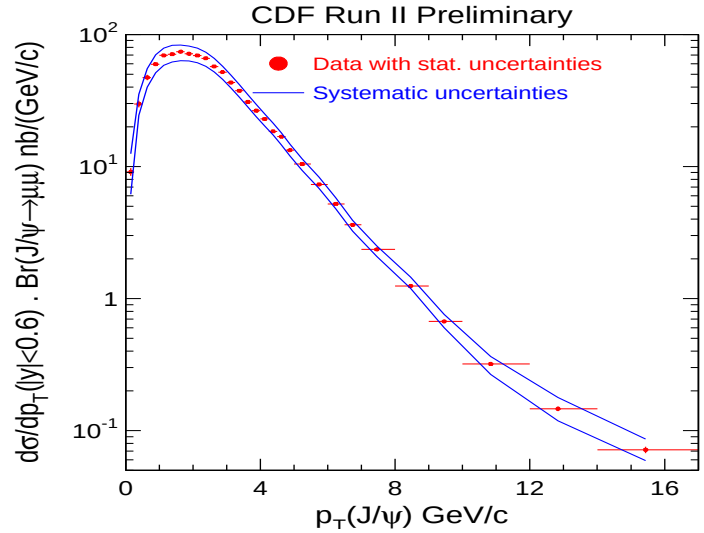




- long standing disagreement ($\times 2$) between measured Run I $B$ cross sections and NLO QCD predictions
- ongoing theoretical effort to incorporate
  - Fixed Order (FO) exact NLO calc. for massive quark
  - Resummation of log $p_T/m_b$ with NLL accuracy
  - Non-perturbative fragmentation functions extracted from LEP and SLC data

  resulted in greatly improved agreement with the data

# $J/\psi$ Inclusive Cross Section

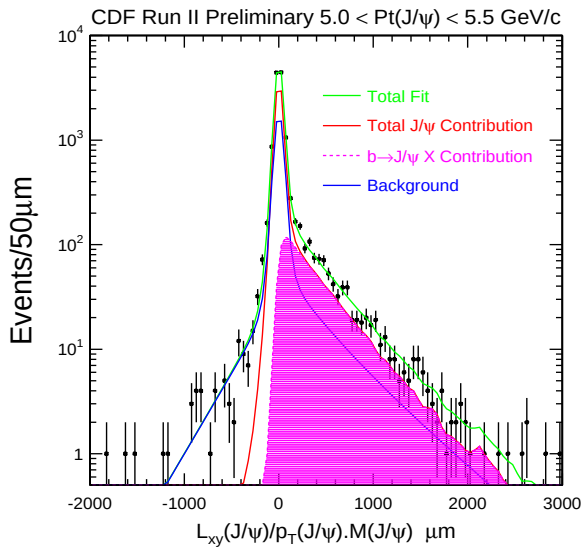


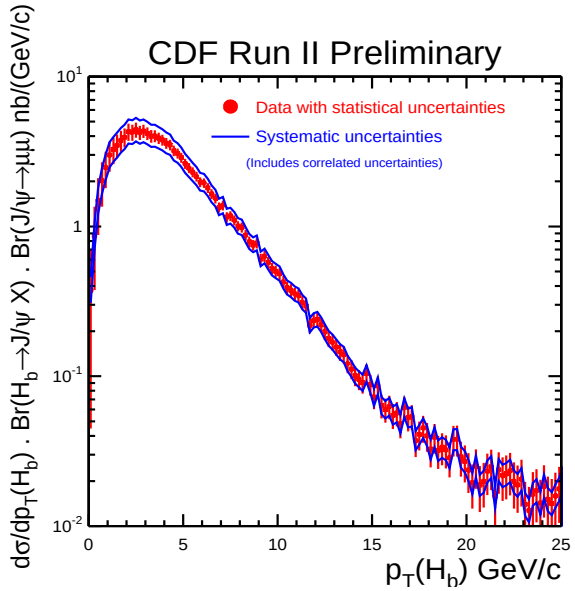



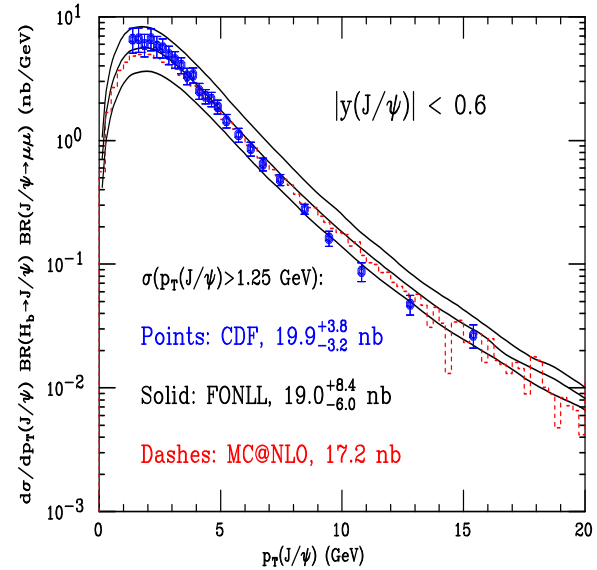

$$\sigma(p\overline{p} \to J/\psi X, |y| < 0.6) =$$
$$4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst)\mu\mathrm{b}$$

- first measurement down to $p_T(J/\psi) \geq 0\mathrm{GeV/c}$
- inclusive: direct $J/\psi$'s and $B \to J/\psi$ decays
- B hadron decays contribute $15 - 20\%$, displaced
- fit for proper time to extract $B$ fraction

# B Hadron Cross Section



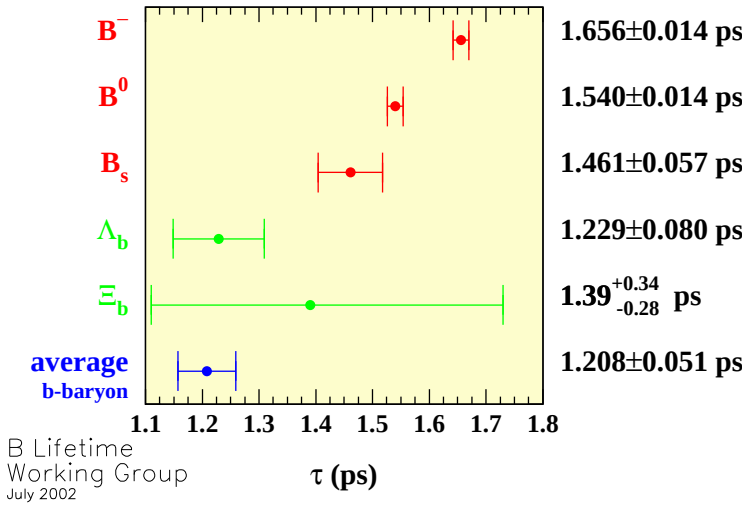

- **lifetime fit extracts $B$ fraction in $p_T$ bins**

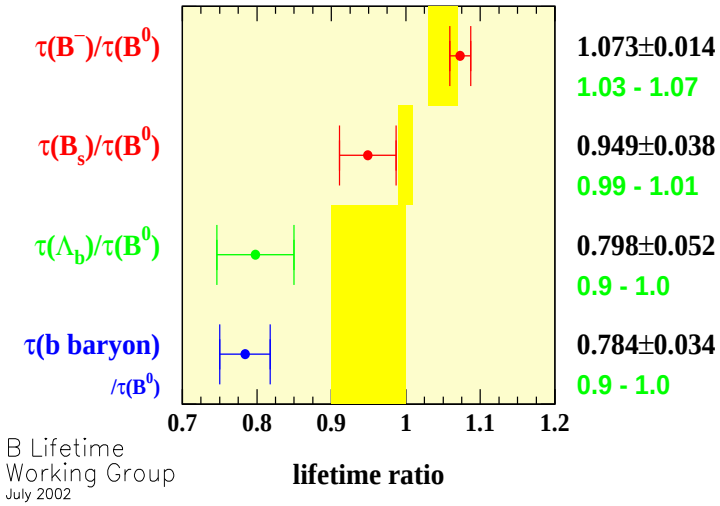
$$\sigma(p\bar{p} \to \bar{b}X, |y| < 1.0) = 29.4 \pm 0.6(stat) \pm 6.2(syst)\mu\mathrm{b}$$

**FONLL:** $\sigma(p\bar{p} \to \bar{b}X, |y| < 1.0) = (27.5^{+11}_{-8.2})\mu\mathrm{b}$

- **largest syst. unc. due to $J/\psi$ polarization**
- **good agreement between data and FONLL prediction (hep-ph/0312132)**

# B Hadron Lifetimes



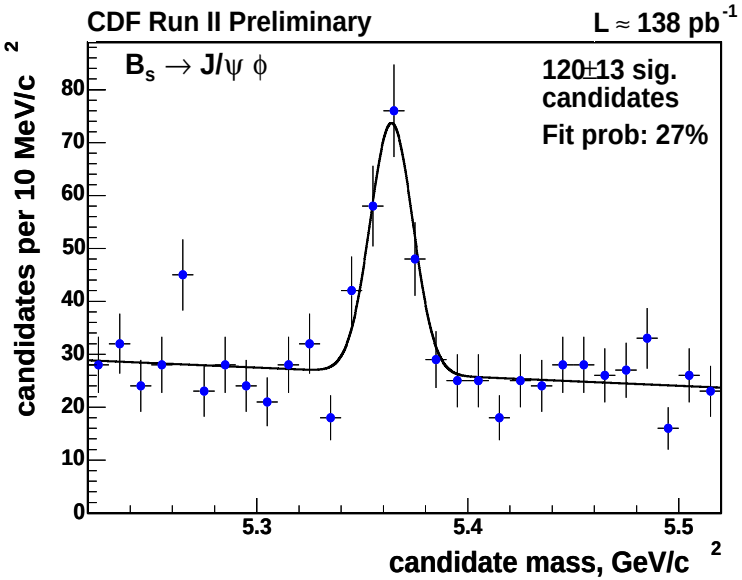



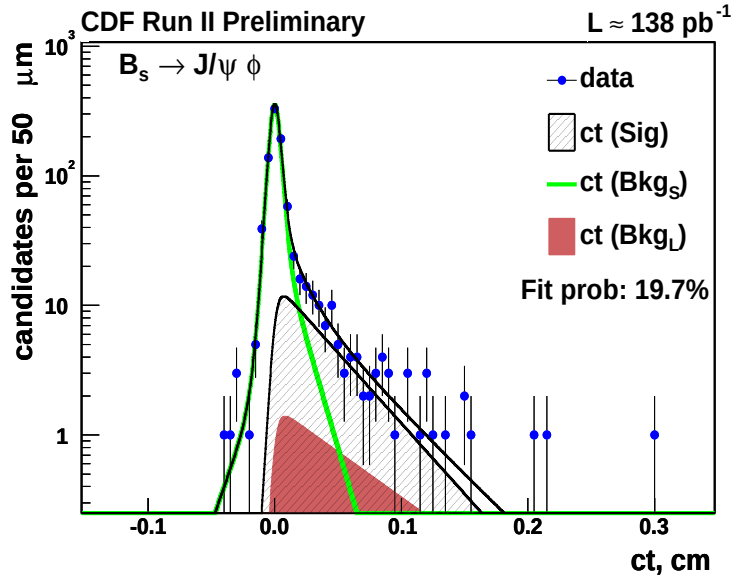

## HQET predicts:

$$\tau_{B^+} \geq \tau_{B^0} \approx \tau_{B^0_s} > \tau_{\Lambda_b} >> \tau_{B^+_c}$$

- $\Lambda_b$ lifetime lower than predictions
- $B^+$, $B^0$ precision measurements at BaBar, Belle
- $B^0_s$ and $\Lambda_b$ only produced at Tevatron

# $B_s^0$ Meson Lifetime

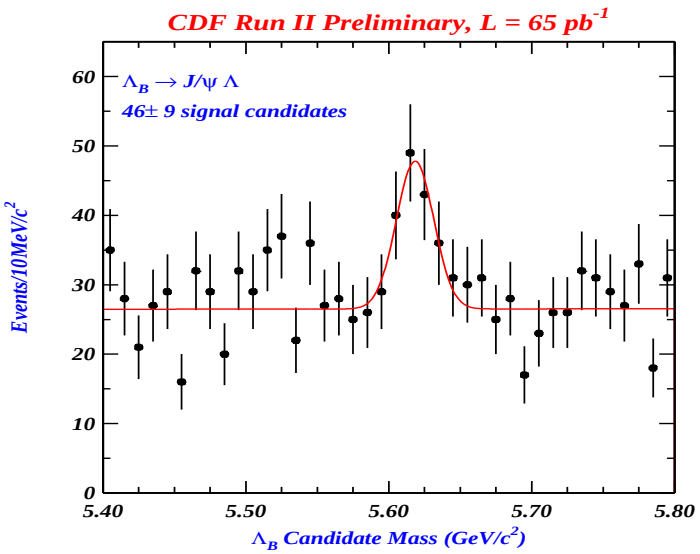


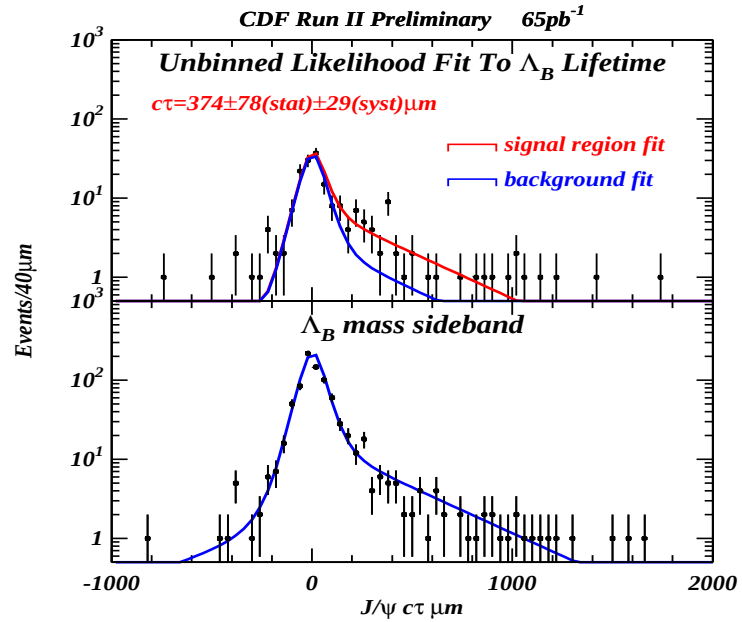




$$\tau(B_s^0) = (1.33 \pm 0.14(stat) \pm 0.02(syst))\text{ps}$$

- $B_s^0 \to J/\psi\phi,\ J/\psi \to \mu^+\mu^-, \phi \to K^+K^-$
- combined mass and lifetime fit
- comparable to world best single measurement
- measurement will improve with more data

# $\Lambda_b$ Lifetime




$$\tau(B_s^0) = (1.25 \pm 0.26(stat) \pm 0.10(syst))\text{ps}$$

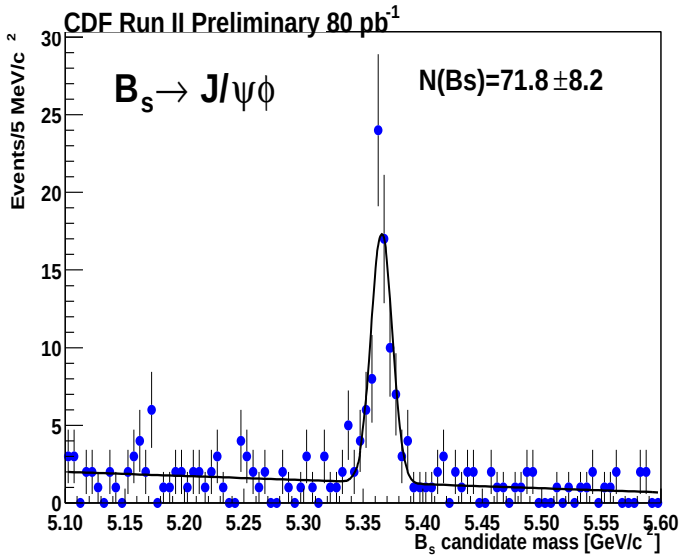
- $\Lambda_b \to J/\psi\Lambda,\ J/\psi \to \mu^+\mu^-, \Lambda \to p\pi$
- first measurement using exclusive $\Lambda_b$ reconstruction
- previous measurements used $\Lambda_c l\nu X$
- statistics limited, will improve in the future

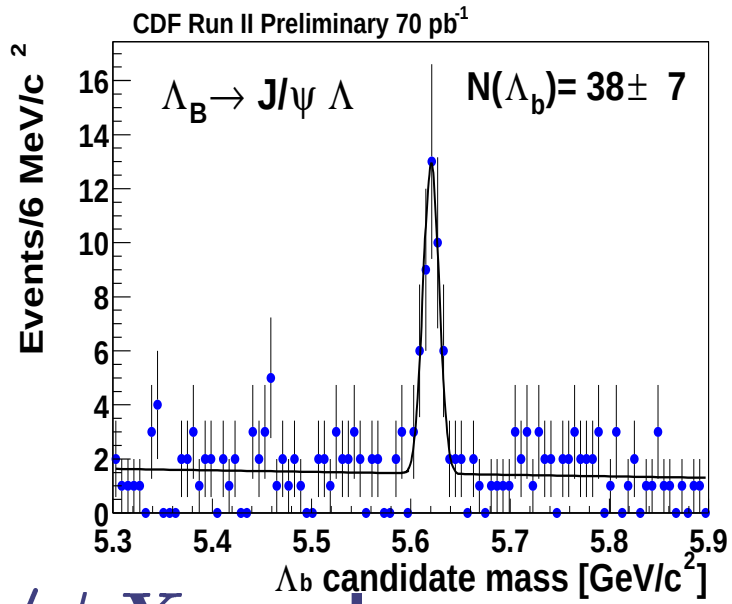
# Lifetime Results Overview

| | CDF [ps] | PDG [ps] |
|---|---|---|
| $B^+$ | $1.63 \pm 0.05(st) \pm 0.04(sys)$ | $1.674 \pm 0.018$ |
| $B^0$ | $1.51 \pm 0.06(st) \pm 0.02(sys)$ | $1.542 \pm 0.016$ |
| $B_s$ | $1.33 \pm 0.14(st) \pm 0.02(sys)$ | $1.461 \pm 0.057$ |
| $\Lambda_b$ | $1.25 \pm 0.26(st) \pm 0.10(sys)$ | $1.229 \pm 0.080$ |

- high statistics ($B^+$, $B^0$) agree with PDG
- $B_s^0$ and $\Lambda_b$ getting competitive with world best single measurements
- main sources of systematic uncertainties:
  - SVX detector alignment
  - resolution function model
- all measurements are statistically limited

# B Hadron Masses




- fully reconstructed $B \to J/\psi X$ modes
- calibration: $J/\psi \to \mu\mu$ and $\psi(2S) \to J/\psi\pi\pi$.
- syst. unc. due to magnetic field, material

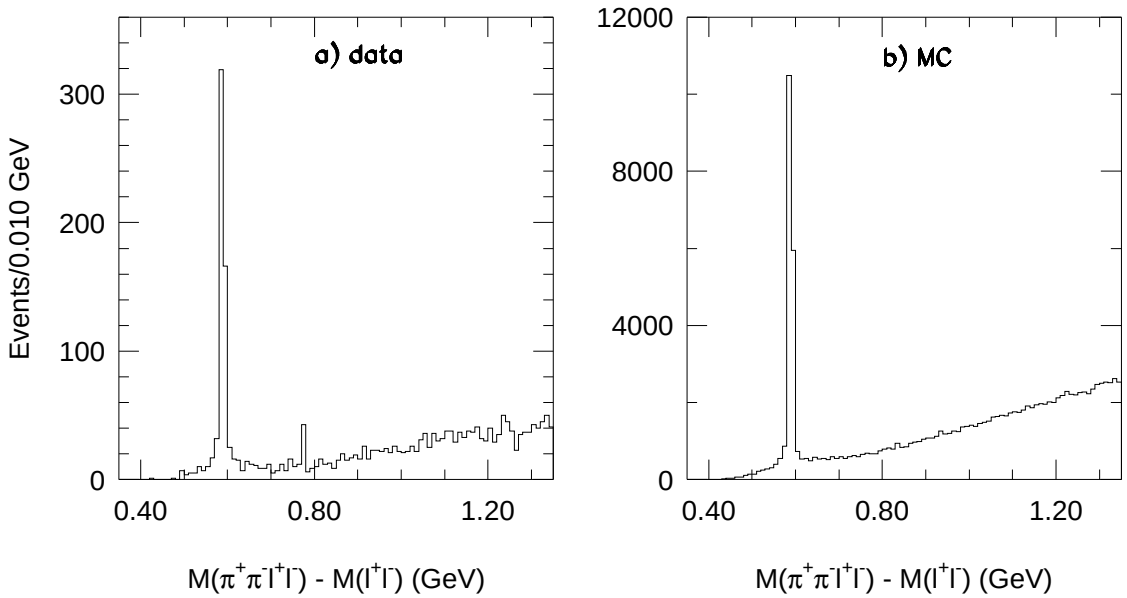
$m(B^0)$=$(5280.30 \pm 0.92 \pm 0.96)\mathrm{MeV/c^2}$

$m(B^+)$=$(5279.32 \pm 0.68 \pm 0.94)\mathrm{MeV/c^2}$

$m(B_s^0)$=$(5365.50 \pm 1.29 \pm 0.94)\mathrm{MeV/c^2}$

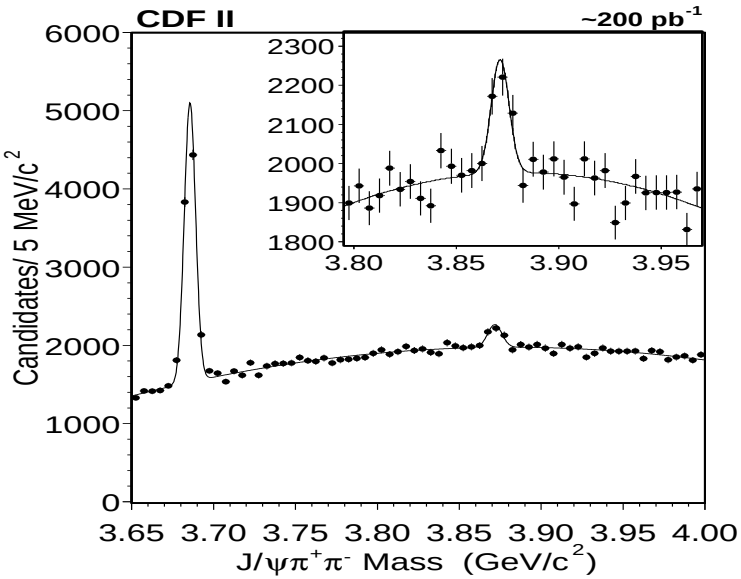
$m(\Lambda_b)$=$(5620.4 \pm 1.6 \pm 1.2)\mathrm{MeV/c^2}$

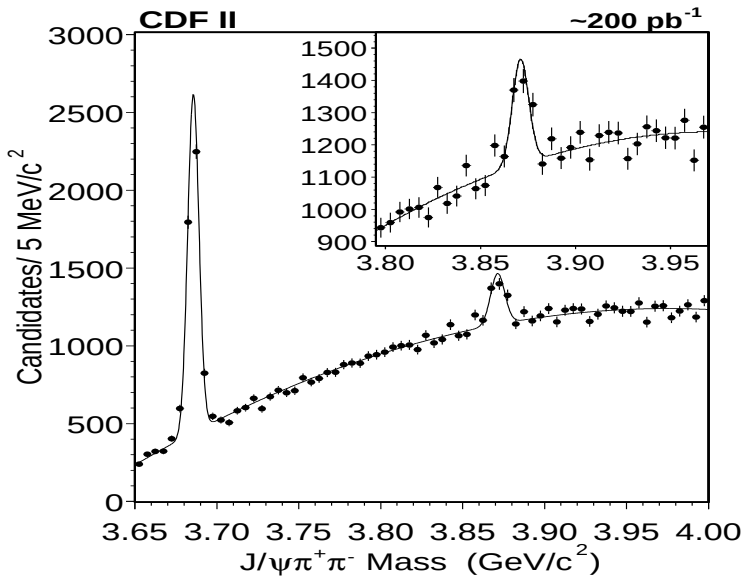
# The $X(3870)$ State ...




- in Oct 2003, Belle announces the observation of a narrow state decaying to $J/\psi\pi^+\pi^-$ (hep-ex/0309032)
- charmonium state? $D^0\overline{D^{0*}}$ molecule?
- confirmation and further studies needed ($\sim 40$ evts reported)

# .. is confirmed



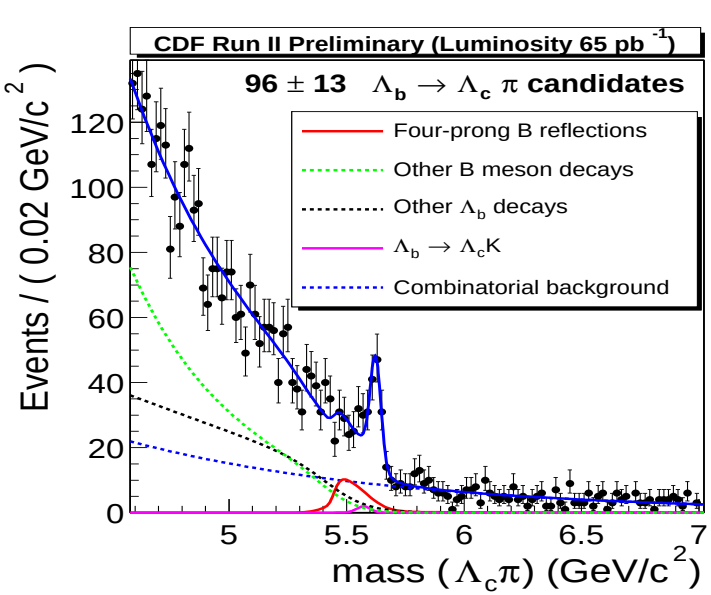

- with 220 $\mathrm{pb}^{-}1$ of data ($\sim$ 2M $J/\psi$) CDF produced first confirmation of the Belle observation
- observed $730 \pm 90$ events

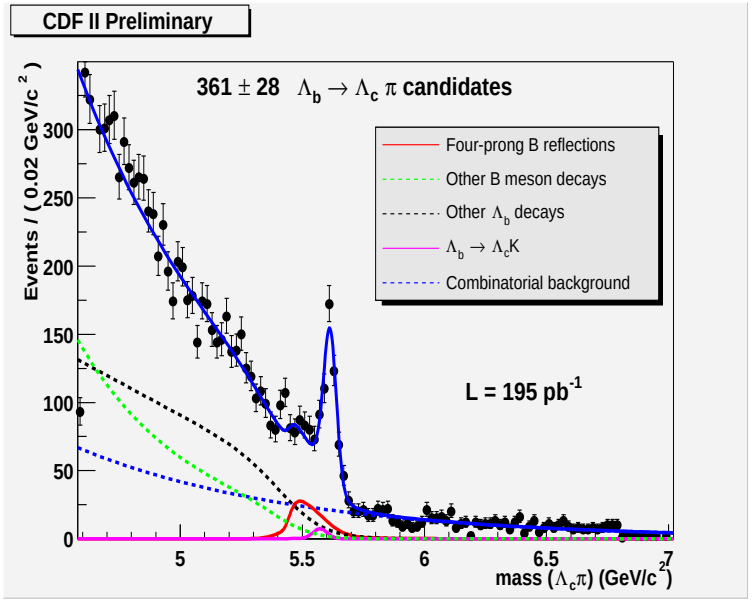
  CDF: $m_{X(3870)} = (3871.3 \pm 0.7 \pm 0.4)\mathrm{MeV/c^2}$

  Belle: $m_{X(3870)} = (3872.0 \pm 0.6 \pm 0.5)\mathrm{MeV/c^2}$
- future studies on the sample:

  lifetime, angular analysis, $M(\pi\pi)$

# $\Lambda_b \to \Lambda_c \pi$ Branching Fraction

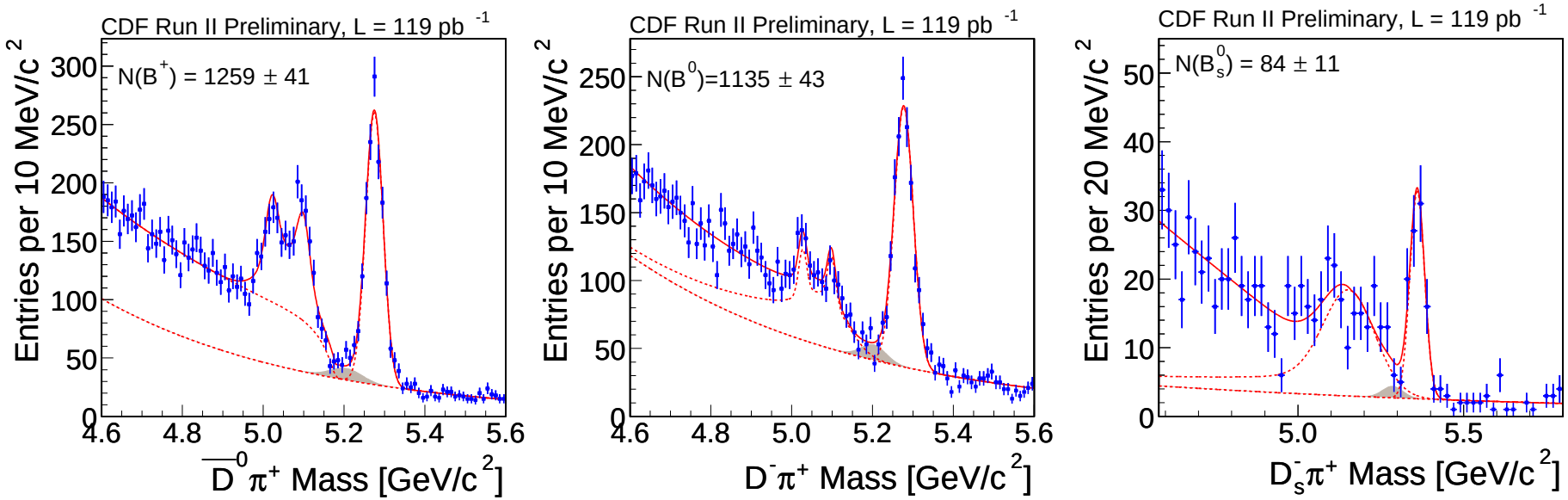


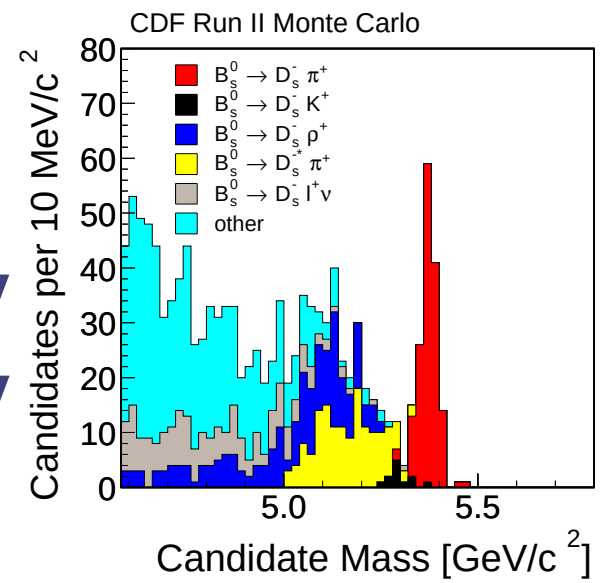

$$Br(\Lambda_b \to \Lambda_c \pi) = (6.0 \pm 1.0(st) \pm 0.8(sys) \pm 2.1(Br)) \cdot 10^{-3}$$

- **measure:**
  $f_{baryon}/f_d \times Br(\Lambda_b \to \Lambda_c \pi)/Br(B^0 \to D^- \pi^+)$
- **kinematically similar final states**
- **extract reflection shapes from Monte Carlo**
- **obtain normalization from fit to data**

# $B_s^0 \to D_s^- \pi$ Branching Fraction



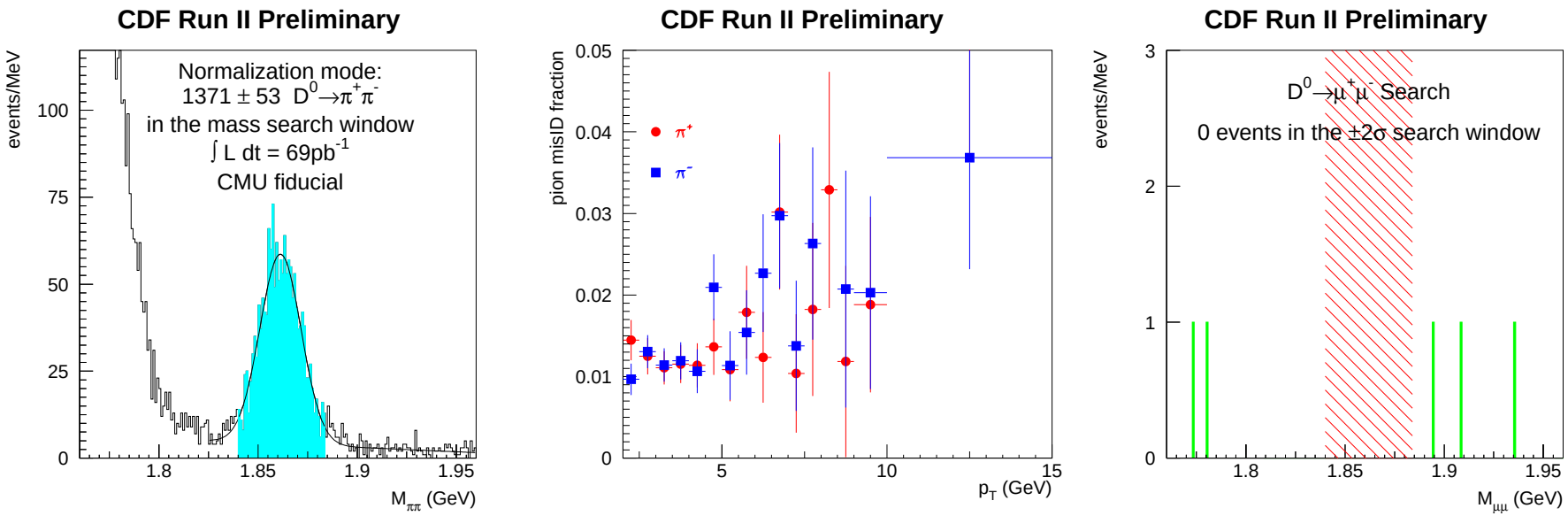

- similar technique as $Br(\Lambda_b)$
- sample size for $B_s^0$ mixing
- measurement limited by $Br(D_s^- \to \phi\pi)$ uncertainty




$$Br(B_s^0 \to D_s^- \pi) =$$

$$(4.8 \pm 1.2(st) \pm 1.8(Br) \pm 0.6(f_s) \pm 0.8(syst)) \cdot 10^{-3}$$

# Rare Decays: $D^0 \to \mu^+\mu^-$



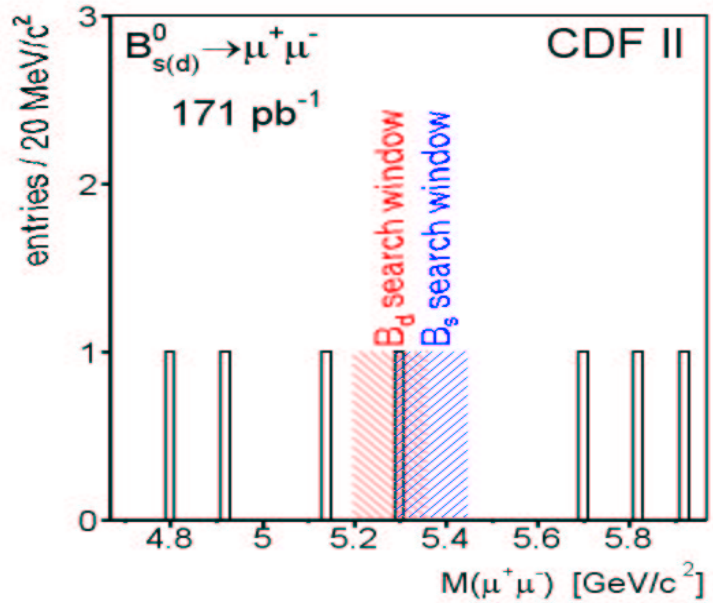

- SM $Br(D^0 \to \mu^+\mu^-) \sim 10^{-13}$
- non-SM physics may enhance the $Br$ to $\sim 10^{-6}$
- search for $D^* \to D^0\pi,\ D^0 \to \mu^+\mu^-$
- main background from $D^0 \to \pi\pi$ decays
- expect $1.8 \pm 0.7$ bkgd events in search window

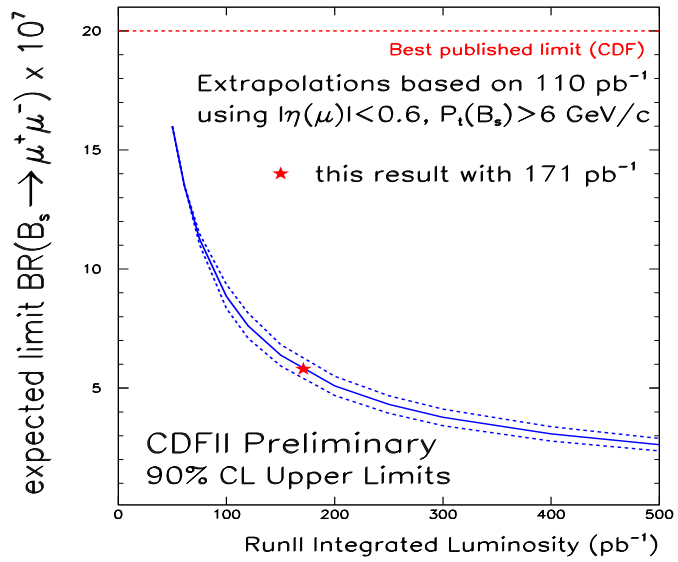
$Br(D^0 \to \mu\mu) \leq 2.4 \times 10^{-6}$ @ 90% CL

about twice better than previous limit

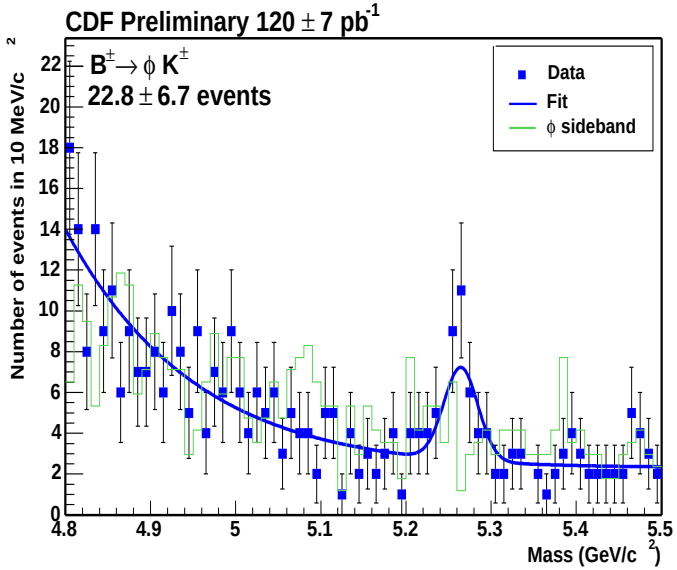
# $B_s^0, B^0 \to \mu^+\mu^-$

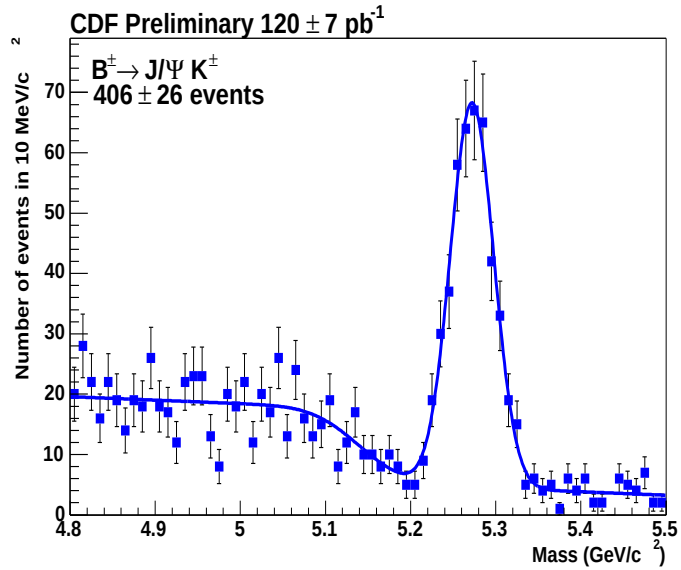
- di-muon rare $B$ trigger
- expected backgrounds:
  $B_s^0 : \; 1.05 \pm 0.30$
  $B^0 : \; 1.07 \pm 0.31$
- observed 1 event
  Branching ratios (90% CL):
  $Br(B_s^0 \to \mu\mu) \leq (5.8 \times 10^{-7})$
  $Br(B^0 \to \mu\mu) \leq (1.5 \times 10^{-7})$
- $B_s^0$ limit factor 3 better than previously published (CDF)
- limit on $B^0$ is slightly better than Belle's



# $B^+ \to \phi K^+$

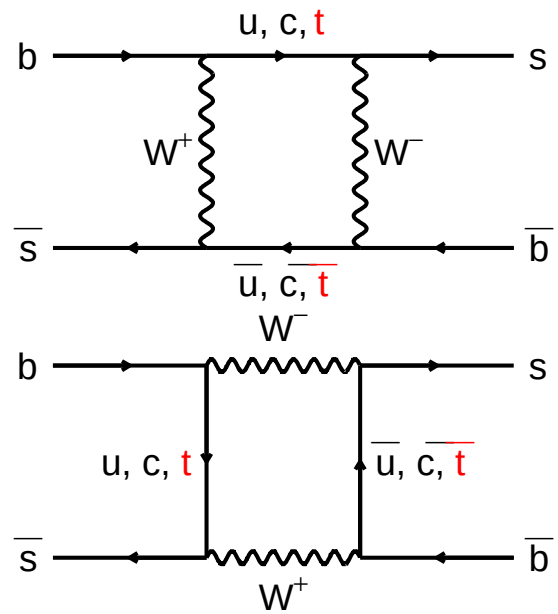


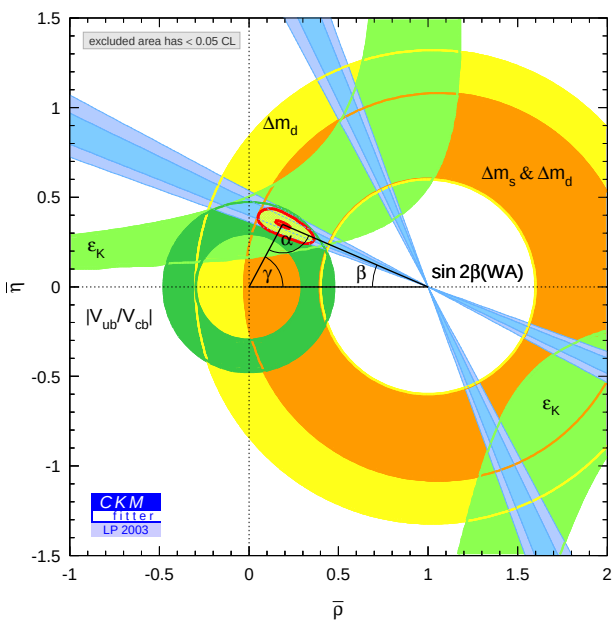




- charmless $B^+$ decay $B^+ \to \phi K^+$
- normalization $B^+ \to J/\psi K^+$ in two-track data
  $Br(B^+ \to \phi K^+) =$
  $(6.9 \pm 2.1(stat) \pm 0.8(syst)) \times 10^{-6}$
- PDG 2002 value: $(7.9^{+2.0}_{-1.8}) \times 10^{-6}$

# $B$ Mixing and the Unitarity Triangle

- both $B_d$ and $B_s$ mesons mix
- ratio of mixing frequencies: **measures one side of the unitarity triangle ($|V_{td}/V_{ts}|$)**
- indir. meas: $\Delta m_s \leq 24\ \mathrm{ps}^{-1}$
- overconstrain $\rightarrow$ **test SM**




**Input for unitarity triangle fits:**

- $CP$ violation in $K, B$ system
- $B \rightarrow \pi l \nu X$ vs $B \rightarrow D l \nu X$
- $B_d$, $B_s$ meson mixing
- direct measurements of $\alpha$, $\gamma$

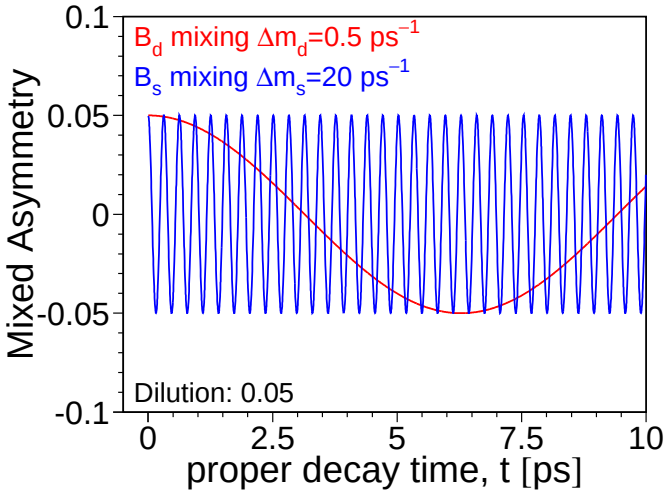
# $B_{(s)}$ Mixing Measurement Ingredients

Per B meson decay,

- determine decay flavor [use flavor specific states]
- identify B meson production flavor [flavor tagging]
- measure B proper decay time [$ct$ resolution]

Time-dependant asymmetry:

$$A_{mix}(t) = \frac{N^{obs}_{unmix}(t) - N^{obs}_{mix}(t)}{N^{obs}_{unmix}(t) + N^{obs}_{mix}(t)} = (2p-1)\cdot\cos(\Delta m \cdot t)$$




Oscillation amplitude: $2p - 1 = D$ [dilution]

$$\text{Significance} = \sqrt{\frac{S\epsilon D^2}{2}} e^{\frac{-(\Delta m)\sigma(c\tau)}{2}} \sqrt{\frac{S}{S+B}}$$

# $B_s^0$ Mixing Reach Estimates

- **Current performance:**
- $S = 1600/\mathrm{fb}^{-1}$, $\mathrm{S/B} = 2:1$
- $\epsilon D^2 = 4\%$, $\sigma(ct) = 67$ fs

**$2\sigma$ sensitivity**
$\Delta m_s = 15\ \mathrm{ps}^{-1}$
**with 500 $\mathrm{pb}^{-1}$**

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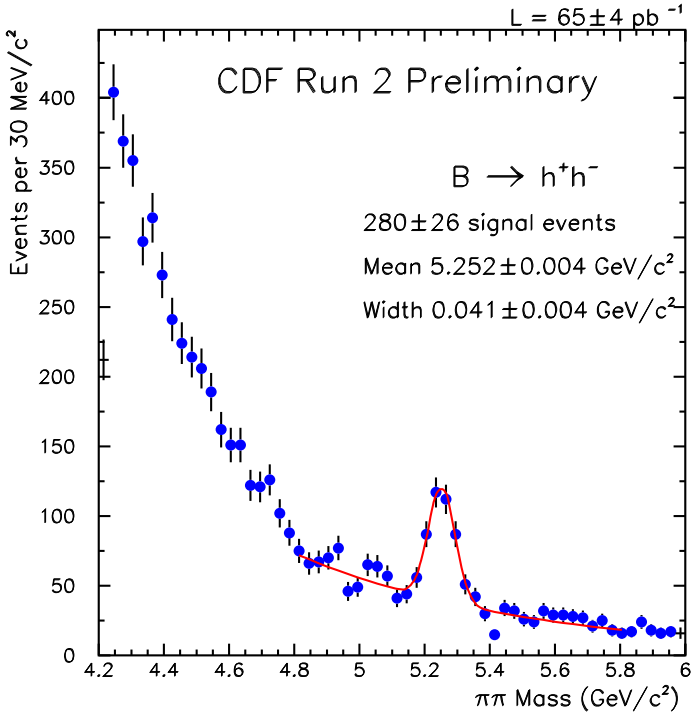
- **With "modest" improvements:**
- $S = 2000/\mathrm{fb}^{-1}$, $\mathrm{S/B} = 2:1$
  **(improve trigger, more modes)**
- $\epsilon D^2 = 4\%$, $\sigma(ct) = 50$ fs
  **(event by event prim vertex, Si on beampipe)**
- **$3\sigma$ for $\Delta m_s = 18\ \mathrm{ps}^{-1}$ with 1.3 $\mathrm{fb}^{-1}$**
- **$5\sigma$ for $\Delta m_s = 18\ \mathrm{ps}^{-1}$ with 1.7 $\mathrm{fb}^{-1}$**
- **$5\sigma$ for $\Delta m_s = 24\ \mathrm{ps}^{-1}$ with 3.2 $\mathrm{fb}^{-1}$**
- **this is a difficult measurement**

# $B \to hh$

- goal: measure angles of the Unitarity Triangle
- angle $\gamma$ can be extracted from $B_s^0 \to KK$ decays
- angle $\alpha$ can be extracted from $B_s^0 \to \pi\pi$ decays




- signal is mixture of:
  $B^0 \to K\pi$
  $B^0 \to \pi\pi$
  $B_s^0 \to KK$
  $B_s^0 \to K\pi$
- ToF does not help
  ($p_T > 2\mathrm{GeV}$)

- disentangle using dE/dX ($1.16\sigma$) and kinematics
- measure BR's first, extract angles later

# $B \to hh$ Results

| Mode | Yield |
|---|---|
| $B^0 \to K\pi$ | $148 \pm 17(stat) \pm 17(syst)$ |
| $B^0 \to \pi\pi$ | $39 \pm 14(stat) \pm 17(syst)$ |
| $B_s^0 \to KK$ | $90 \pm 17(stat) \pm 17(syst)$ |
| $B_s^0 \to K\pi$ | $3 \pm 11(stat) \pm 17(syst)$ |

$$\frac{Br(B^0 \to \pi\pi)}{Br(B^0 \to K\pi)} = 0.26 \pm 0.11(stat) \pm 0.06(syst)$$

$$\frac{Br(B_s^0 \to KK)}{Br(B^0 \to K\pi)} = 3.71 \pm 0.73(stat) \pm 0.35(f_s) \pm 0.06(syst)$$

$$A_{CP} = \frac{N(\overline{B^0} \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B^0} \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} =$$

$$= 0.02 \pm 0.15(stat) \pm 0.02(syst)$$

BaBar measures $A_{CP} = -0.102 \pm 0.05 \pm 0.02$

# Conclusions

- new $B$ cross section, precision heavy hadron masses, lifetimes and branching ratios measurements from CDF
- confirmation of Belle's X(3870)
- best limits on $D^0 \to \mu\mu$ and $B_s^0 \to \mu\mu$ decays
- hadronic $B$ trigger provides wealth of $B$ and $D$ decays
- results obtained with 33-80% of available data
- expected improvements:
  - improved SI standalone tracking
  - use of Layer 00
  - event by event primary vertex determination