Beauty and charm decay physics at CDF

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Why B physics at $p\bar{p}$ collider

Open wide spectrum of B hadrons
$B^{\pm}$, B^0, B_s, B_c, Λ_b, Ξ_b

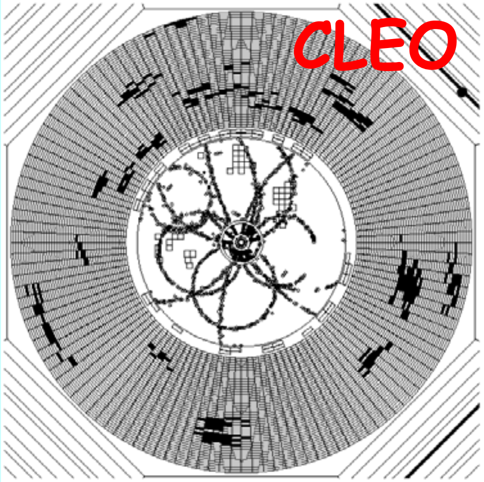
$b\bar{b}$ cross section is 50-100 μb
~O(10^5) larger than @Υ(4S)/Z^0

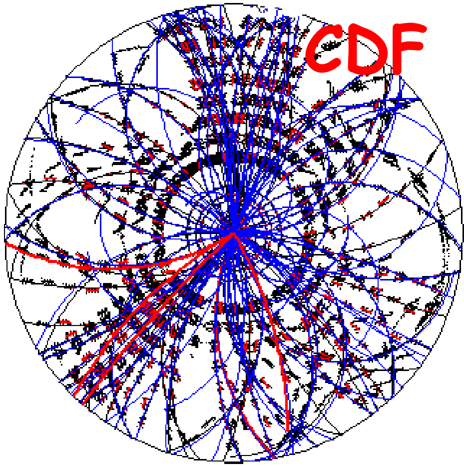
$c\bar{c}$ cross section even larger
(x10 $b\bar{b}$ cross section)

See Peter J. Bussey's talk on
Charm and Beauty production at CDF

BUT:
B hadrons are hidden in a 10^3 larger background ($\sigma_{inelastic}(p\bar{p}) \approx 50$ mb)

Events more complicated than at Υ(4S)





Crucial detector components:
- Tracking system
  Excellent pt res./Vertexing
- Trigger
  Large bandwidth
  Strong background reduction
- Particle identification

CDF Detector in Run II

Inherited from Run I:

Central Calorimeter ($|\eta|<1$)

Solenoid (1.4T)

Partially New:

Muon system (extended to $|\eta|\sim1.5$)

Completely New:

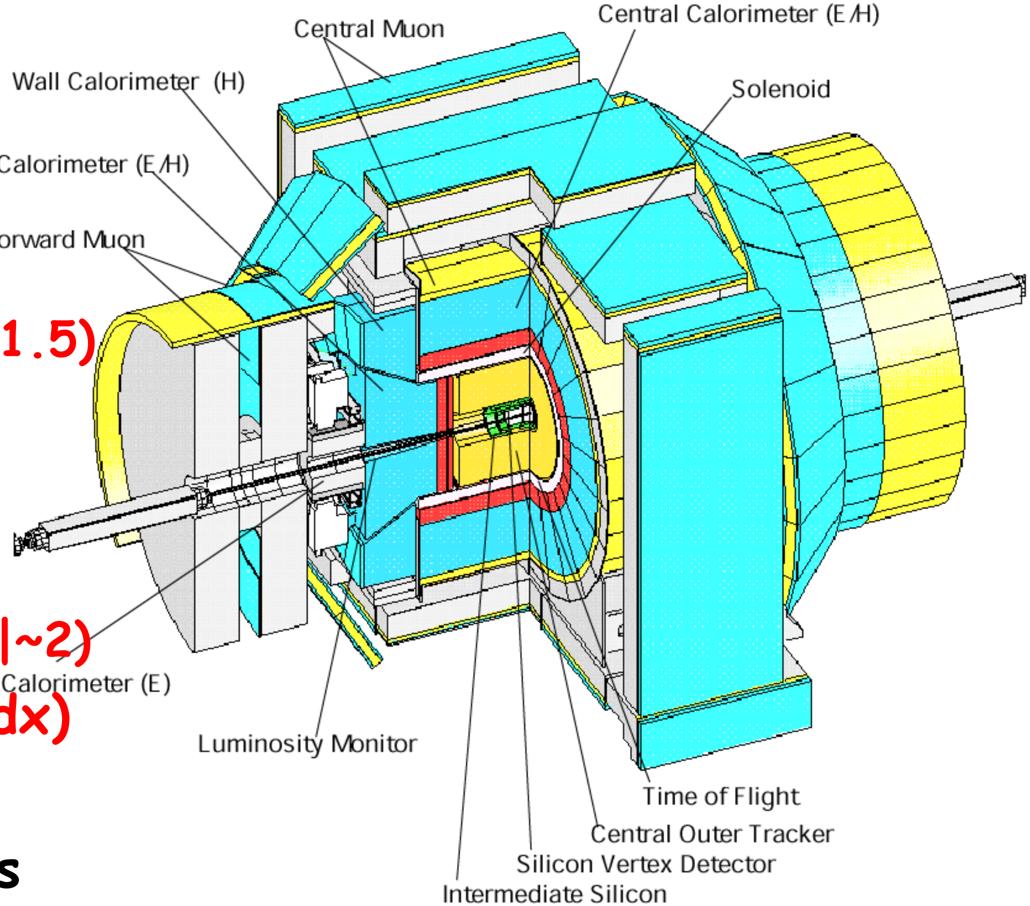
Tracking System

- 3D Silicon Tracker (up to $|\eta|\sim2$)
- Faster Drift Chamber (dE/dx)

Time-of-Flight (particle ID)

Plug and Forward Calorimeters

DAQ & Trigger system (Online Silicon Vertex Tracker: trigger on displaced vertices, first time at hadron collider)



Tevatron $p\bar{p}$ collider

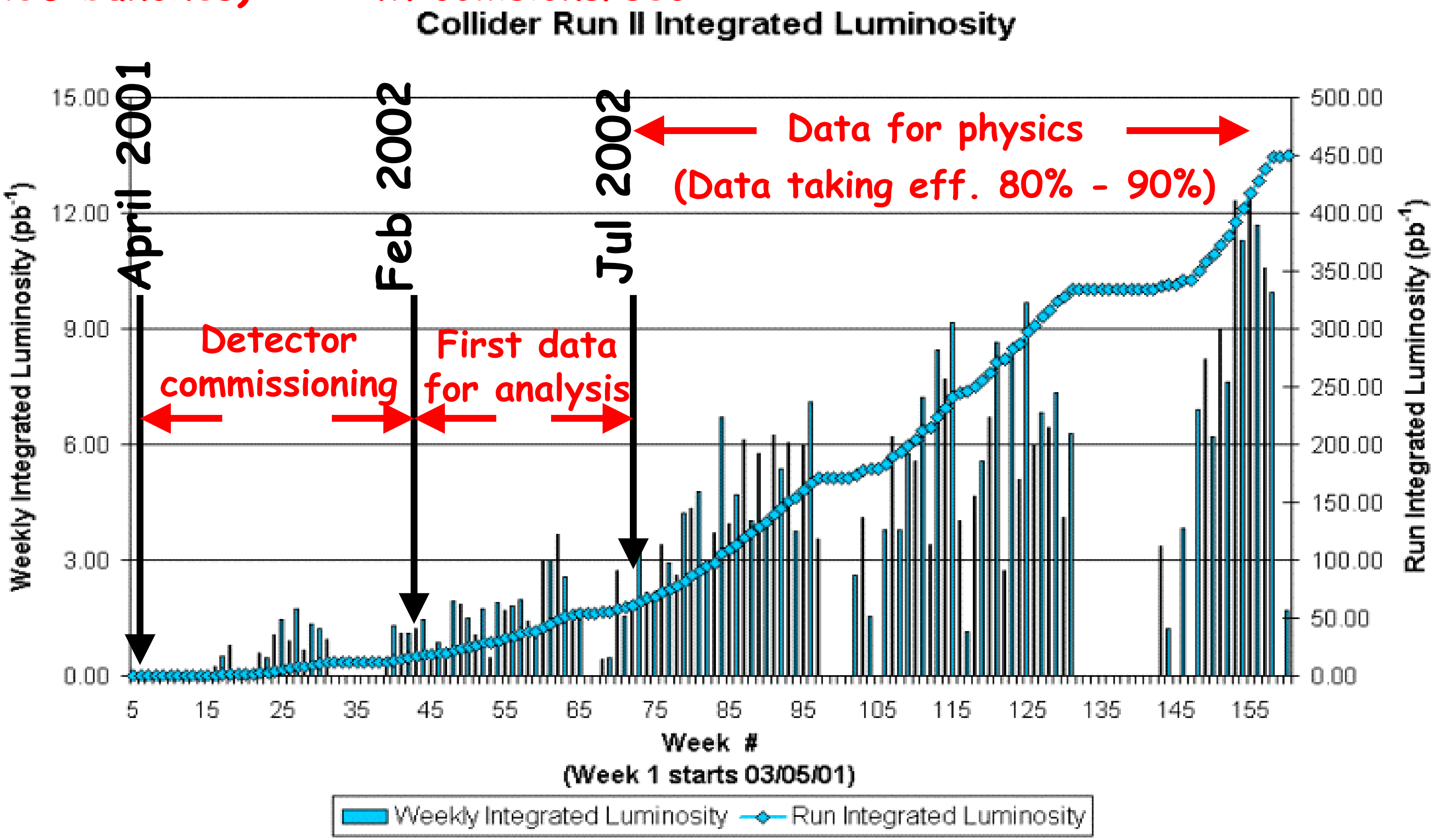
Center of mass energy: 1.96 TeV

Collision rate: 396 ns crossing time

(36x36 bunches) → ~2M collisions/sec

Peak Luminosity: ~7E31

Goal was 8E31 w/o Recycler



CDF analyses reported in this talk use ~65 to ~190 pb^{-1}

Triggers and data samples

(Conventional)

Di-Muon (J/ψ)

Pt(μ) > 1.5 GeV

J/ψ modes down to low Pt(J/ψ) (~ 0 GeV)

- Masses, lifetimes (fully rec. $B \rightarrow J/\psi X$)
- Quarkonia, rare decays ($B_{S(d)} \rightarrow \mu\mu$)

(Unconventional)

Displaced trk + lepton (e, μ)

IP(trk) > 120μm

Pt(lepton) > 4 GeV

Semileptonic modes

- High statistics lifetime
- Sample for tagging studies, mixing

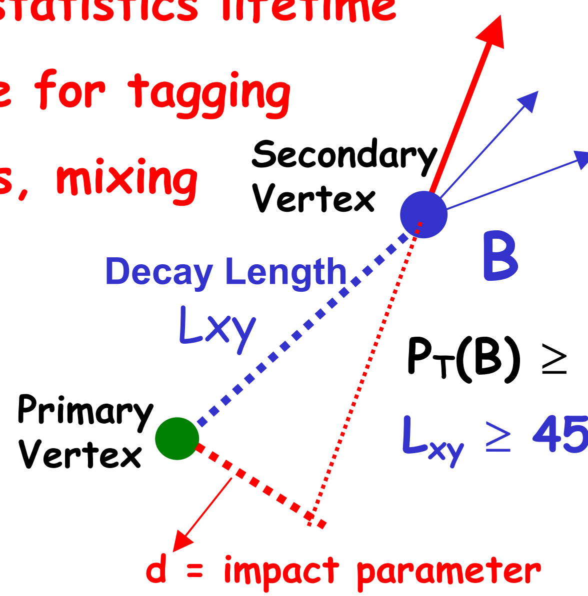
2-Track Trig.

Pt(trk) > 2 GeV

IP(trk) > 100 μm

Fully hadronic modes

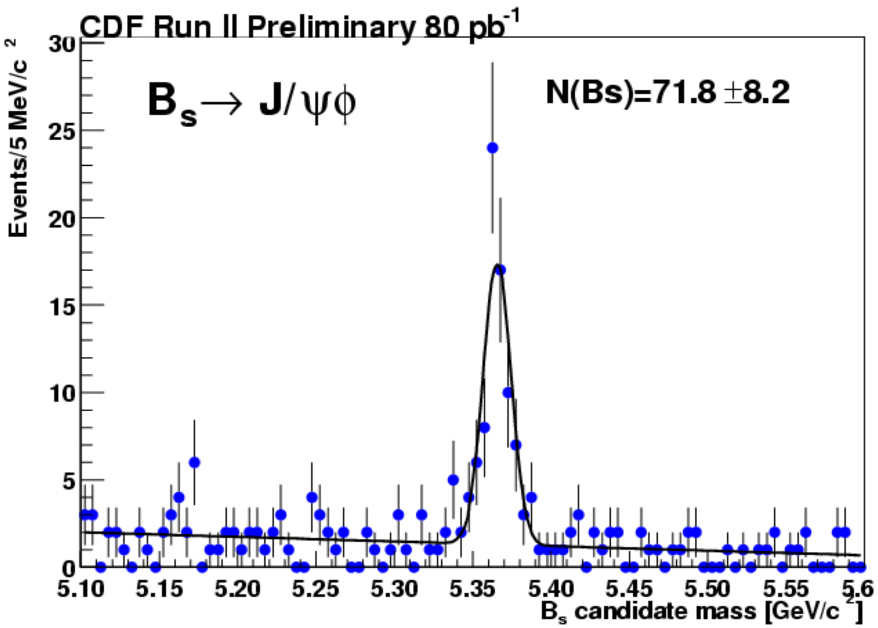
- CP asymmetry in 2-body/multibody charmless decays
- B_s mixing
- Charm physics

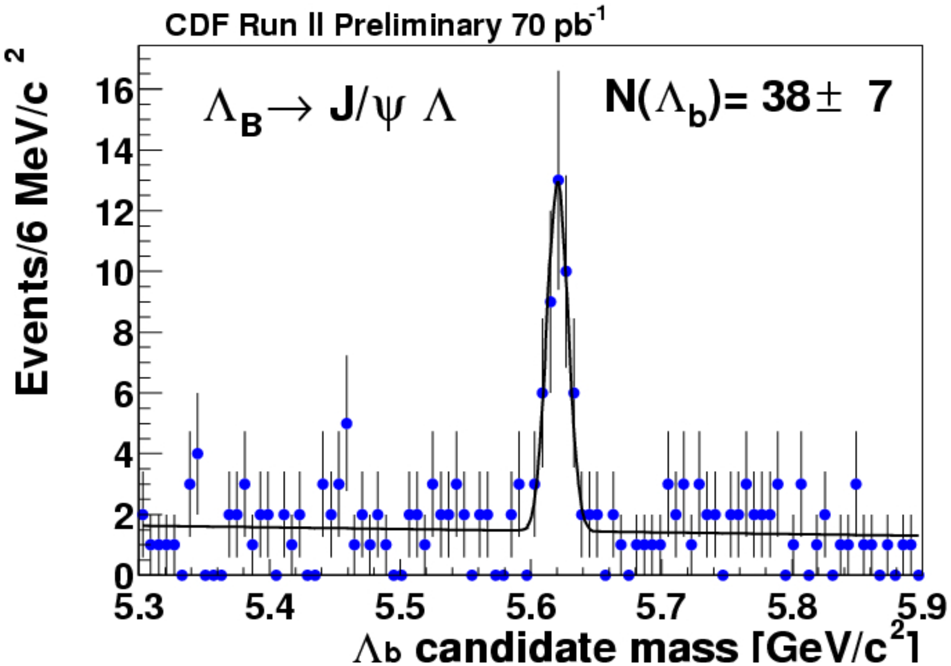


$P_T(B) \geq 5$ GeV

$L_{xy} \geq 450\mu m$

B hadron masses measurements





Competitive measurements for B_d and B^+:

$M(B_d) = 5280.30 \pm 0.92 \pm 0.96\ MeV/c^2$

$M(B^+) = 5279.32 \pm 0.68 \pm 0.94\ MeV/c^2$

World's best measurements for B_s and Λ_b:

$M(B_s) = 5365.50 \pm 1.29 \pm 0.94\ MeV/c^2$

$M(\Lambda_b) = 5620.4 \pm 1.6 \pm 1.2\ MeV/c^2$

B Lifetimes

Heavy Quark Expansion predictions for B lifetimes:

$\tau(B_c) << \tau(\Xi_b^0) \sim \tau(\Lambda_b) < \tau(B^0) \sim \tau(B_s) < \tau(B^-) < \tau(\Xi_b^-) < \tau(\Omega_b)$

HQE gives precise predictions for lifetime ratios - good testing ground:

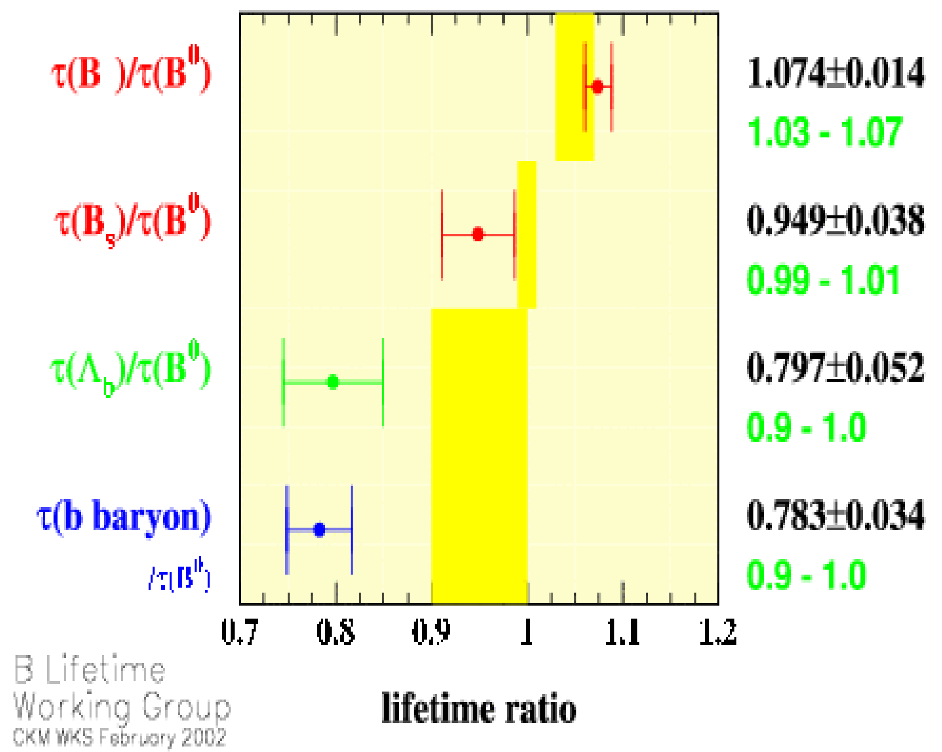
$\tau(B^+)/\tau(B^0)$ = 1.067 ± 0.027

$\tau(B_s)/\tau(B^0)$ = 0.998 ± 0.015

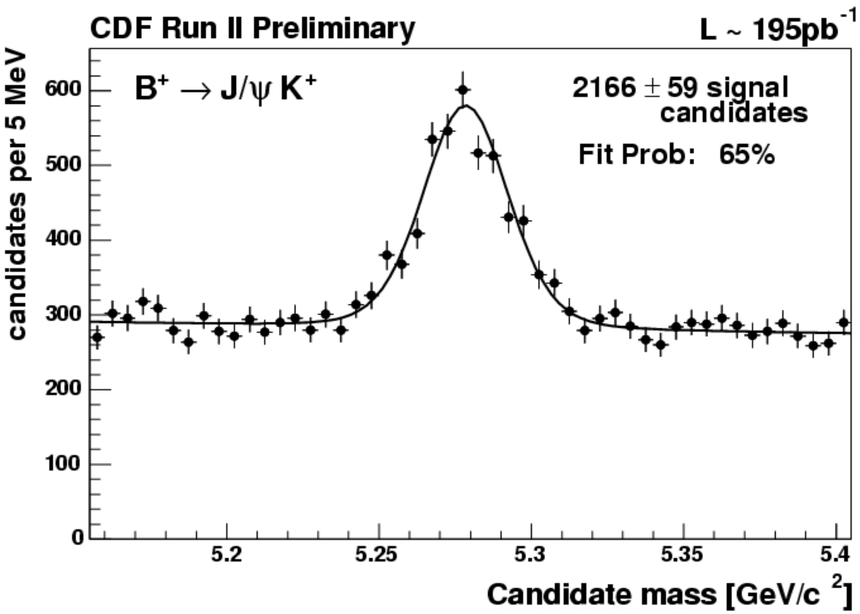
$\tau(\Lambda_b)/\tau(B^0)$ = 0.90 ± 0.05

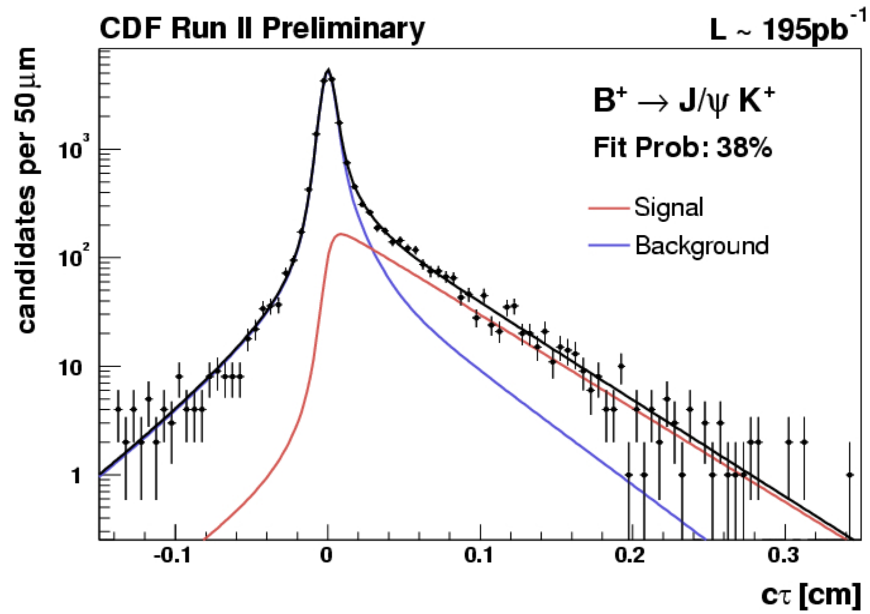
CDF is now approaching Run I precision and is currently limited only by statistics.

Run II will provide real test of HQE



Exclusive B → J/ψ K lifetime





$B^+ \to J/\psi K^+$ 2160 events

$B^+ \to J/\psi K^{*+}$ ($K^{*+} \to K_s \pi$) 200 events

$B^0 \to J/\psi K^{*0}$ ($K^{*0} \to K \pi$) 950 events

$B^0 \to J/\psi K_s$ 600 events

Unbinned simultaneous fit of

M_B: extract signal fraction

ct: extract the lifetime

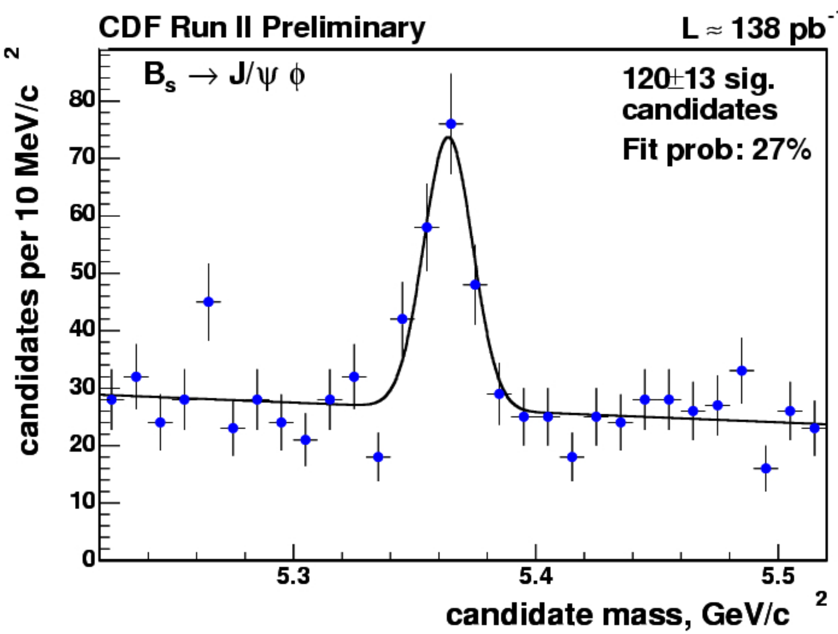
$\tau(B^+) = 1.66 \pm 0.04(stat) \pm 0.02(sys)$ ps

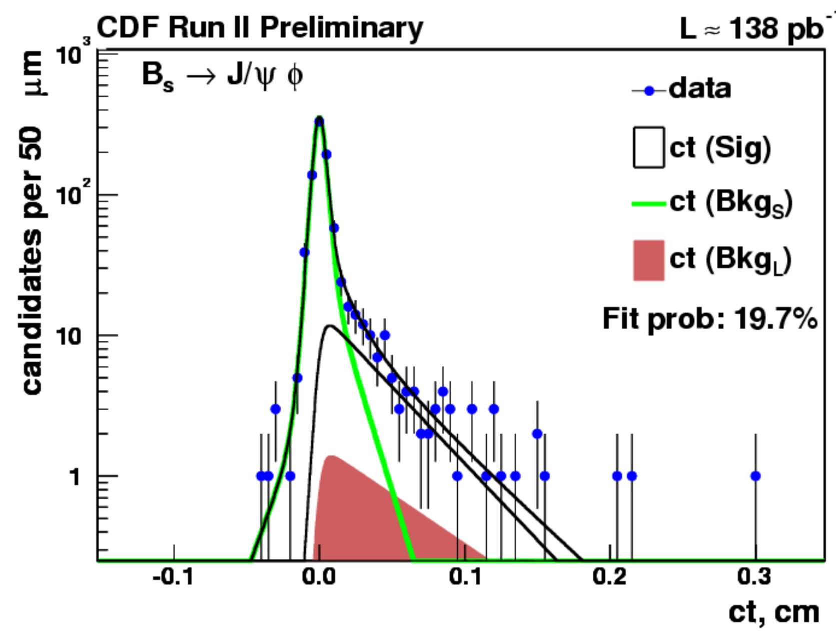
$\tau(B^0) = 1.49 \pm 0.05(stat) \pm 0.03(sys)$ ps

$\tau(B^+)/\tau(B^0) = 1.119 \pm 0.046(stat) \pm 0.014(sys)$

Largest systematic error from background model

Exclusive $B_s \to J/\psi\,\phi$ lifetime (B$_s$ Unique to Tevatron)





$\tau(Bs) = 1.33 \pm 0.14(stat) \pm 0.02(sys)$ ps

$\tau(Bs)/\tau(B^0) = 0.88 \pm 0.11(stat)$

With more statistics

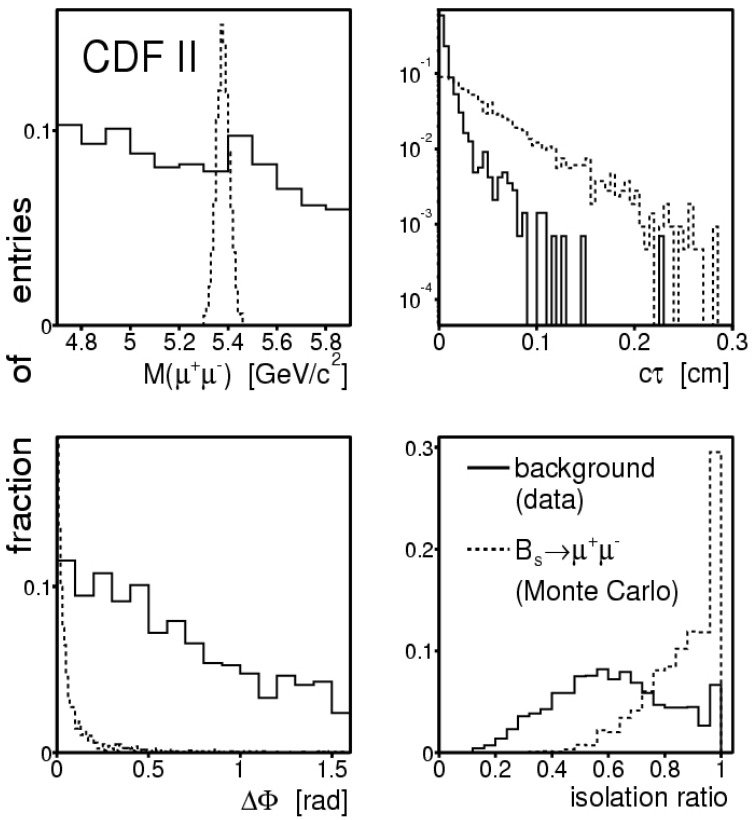
Angular analysis measures $\Delta\Gamma_s = B_s^H - B_s^L$

Large CP asymmetry (measures phase of V_{ts})

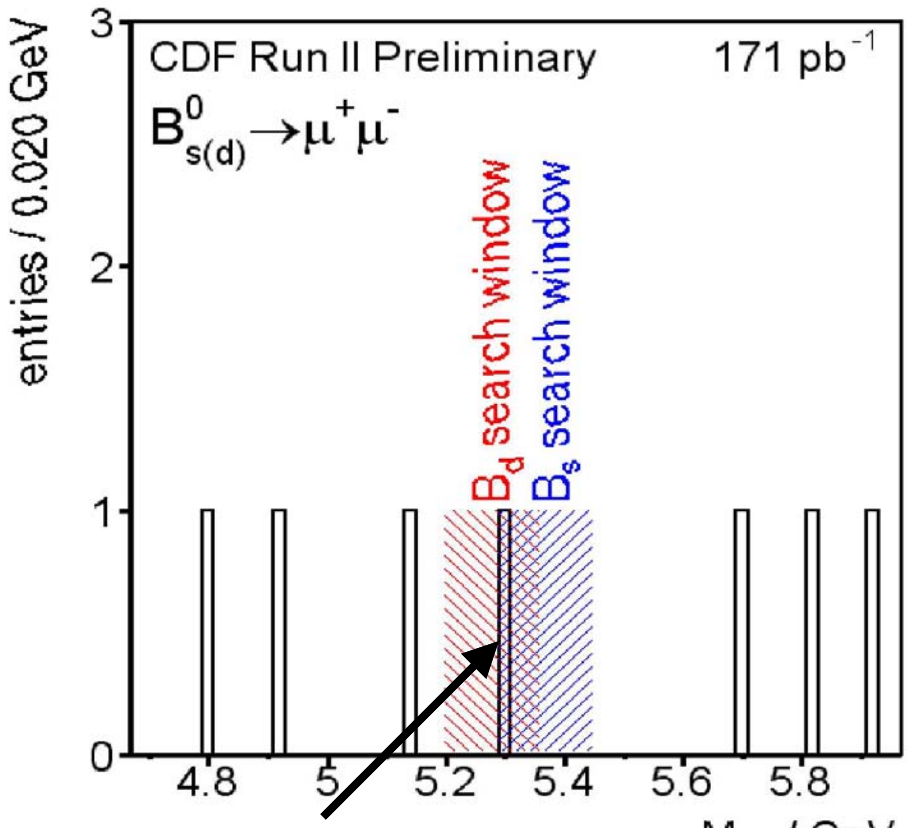
is a signal of new physics (requires Δm_s)

Rare decays: $B_{d(s)} \rightarrow \mu^+\mu^-$

Standard Model predicts $BR(B_s \rightarrow \mu^+\mu^-) = (3.8 \pm 1.0) \times 10^{-9}$
Several SM extensions predict an enhancement by 1 to 3 orders of magnitude: no excess already constrains several SUSY models

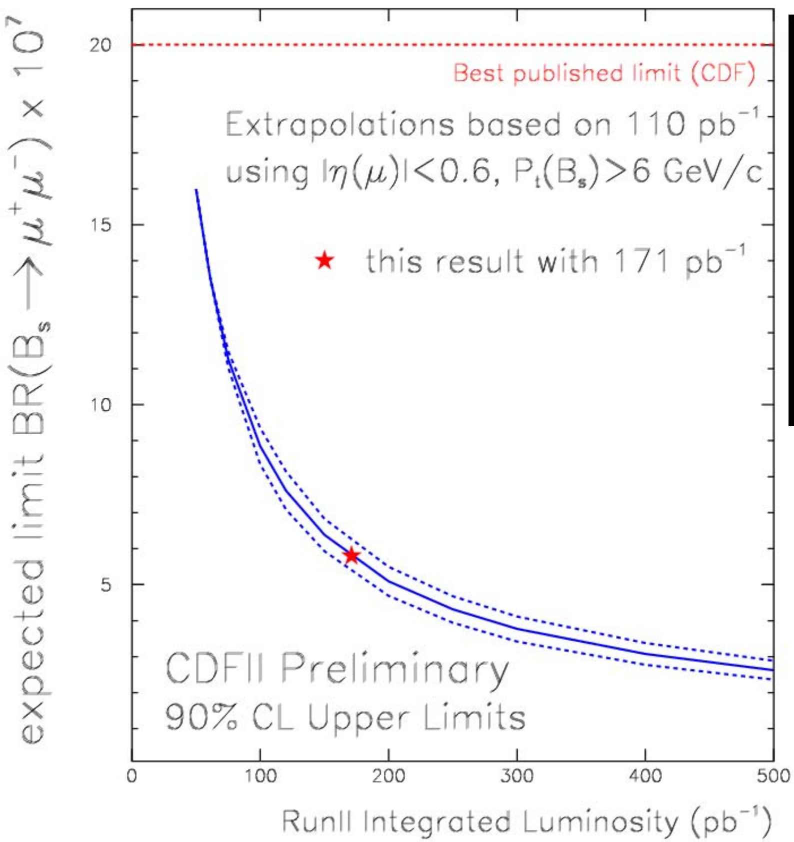


"Blind" analysis: cuts were optimized before looking at the signal mass region



1 event in the overlap region

Rare decays: $B_{d(s)} \to \mu^+\mu^-$



Measured/Expected BR limits vs. luminosity

	$B_s \to \mu^+\mu^-$	$B_d \to \mu^+\mu^-$
Background	1.05±0.30	1.07±0.31
Data	1	1
BR limit @95% C.L.	7.5×10^{-7}	1.9×10^{-7}
BR limit @90% C.L.	5.8×10^{-7}	1.5×10^{-7}

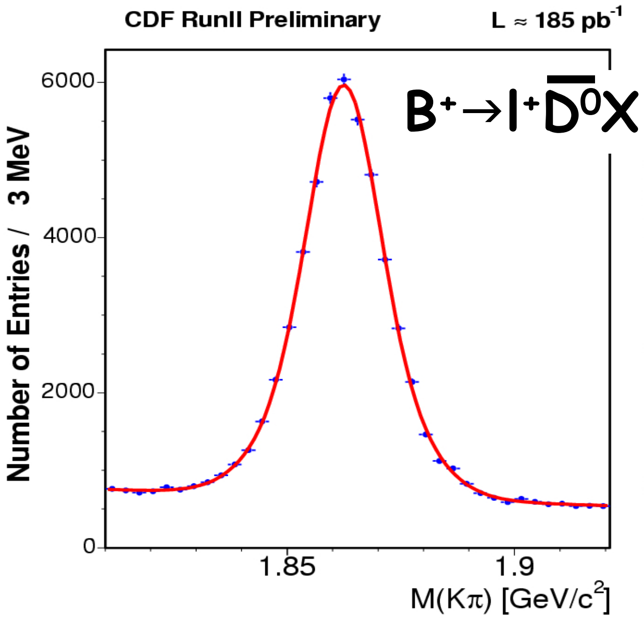
Best world result for B_s (improves CDF Run I)

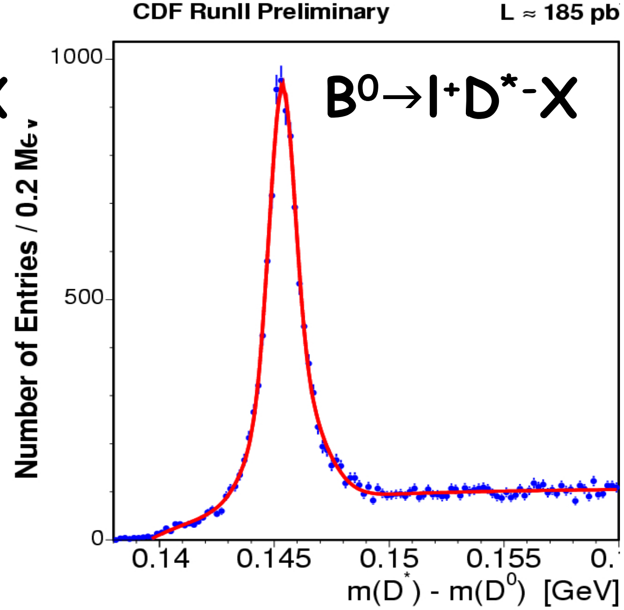
Slightly better results than Belle and BaBar for Bd

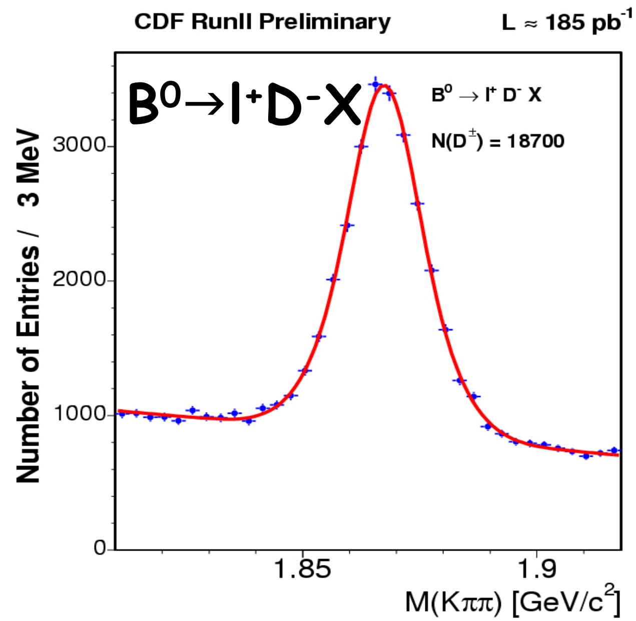
1.6×10^{-7}

2.0×10^{-7}

B^+/B^0 from lepton+displaced track







CDF: high statistics semileptonic B samples

Excellent calibration samples for B^+/B^0 lifetime, tagging and B^0 mixing

$B \to lD^0X$ ($D^0 \to K\pi$): ~41,800 events

$B \to lD^{*+}X$ ($D^{*+} \to D^0\pi$): ~8,400 events

$B \to lD^+X$ ($D^+ \to K\pi\pi$): ~18,700 events

Run II yields significantly larger, lower lepton pt threshold possible thanks to i.p trigger

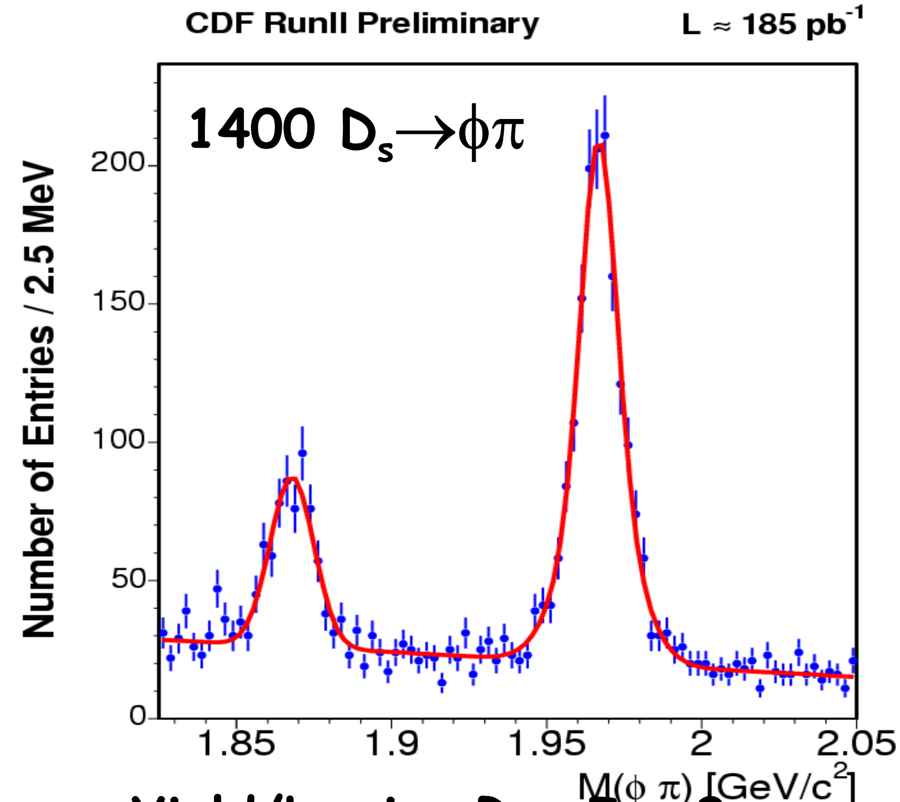
B_s from lepton + displaced track

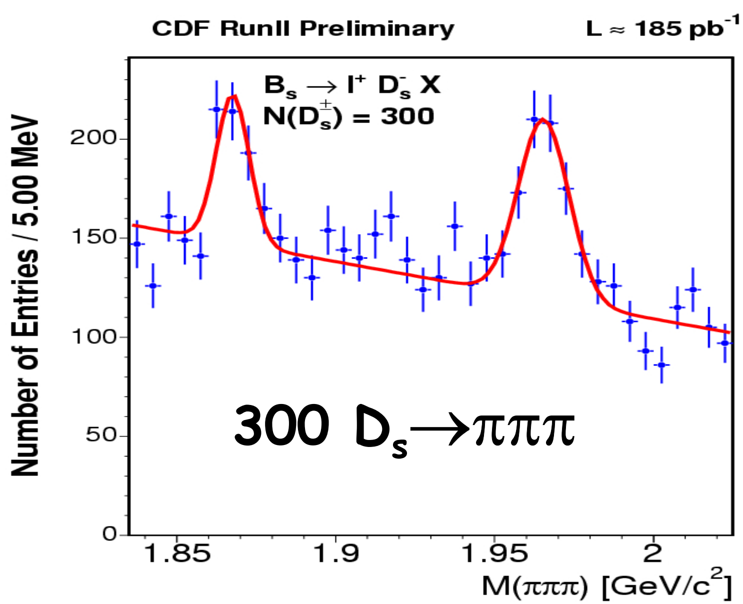
$B_s \rightarrow D_s l\nu \rightarrow [\phi\pi]\, l\nu \rightarrow [[KK]\,\pi] l\nu$ **ONLY @ Tevatron**

HIGH STATISTICS SAMPLE:

- Inclusive lifetime: $\rightarrow \frac{\tau(B_s)}{\tau(B_d)}$
- Mixing (moderate x_s):

  good S/N, limited time resolution: back-up sample





Yield/Lumi ~ Run I x 3

S/N ~ Run I x 2

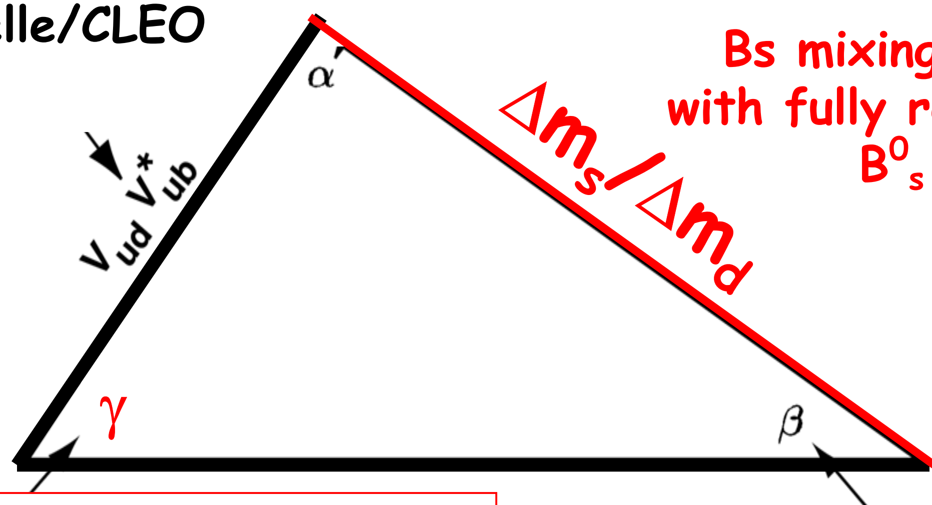
Several D_s channels reconstructed

$D_s \rightarrow \phi\pi$, $D_s \rightarrow \pi\pi\pi$, $D_s \rightarrow KsK$, $D_s \rightarrow K^*K$

Unique to CDF hadronic trigger

$b \to u \ell \nu$

BaBar/Belle/CLEO



Bs mixing is doable at CDF
with fully reconstructed decays
$B^0_s \to D^-_s \pi^+(3\pi)$

Bd $\to \pi\pi$, $K\pi$, Bs $\to$ KK,$K\pi$

$B \to \psi K_S$ BaBar/Belle/CDF/D0

$B^+ \to D^0_{cp} K$

$Bs \to D_S^- K^+$

Bd BaBar/Belle/CDF

Bs Unique to CDF

CDF has unique access to Bs fully hadronic decays
(crucial for CP violation and Bs mixing)
Also huge samples of hadronic charm signals
(CDF results are competitive with charm dedicated experiments)

$B \to h^+h'^-$: towards γ and direct A_{CP}

Measure relative fractions of

$B^0_d \to \pi^+\pi^-$ and charge conjugate

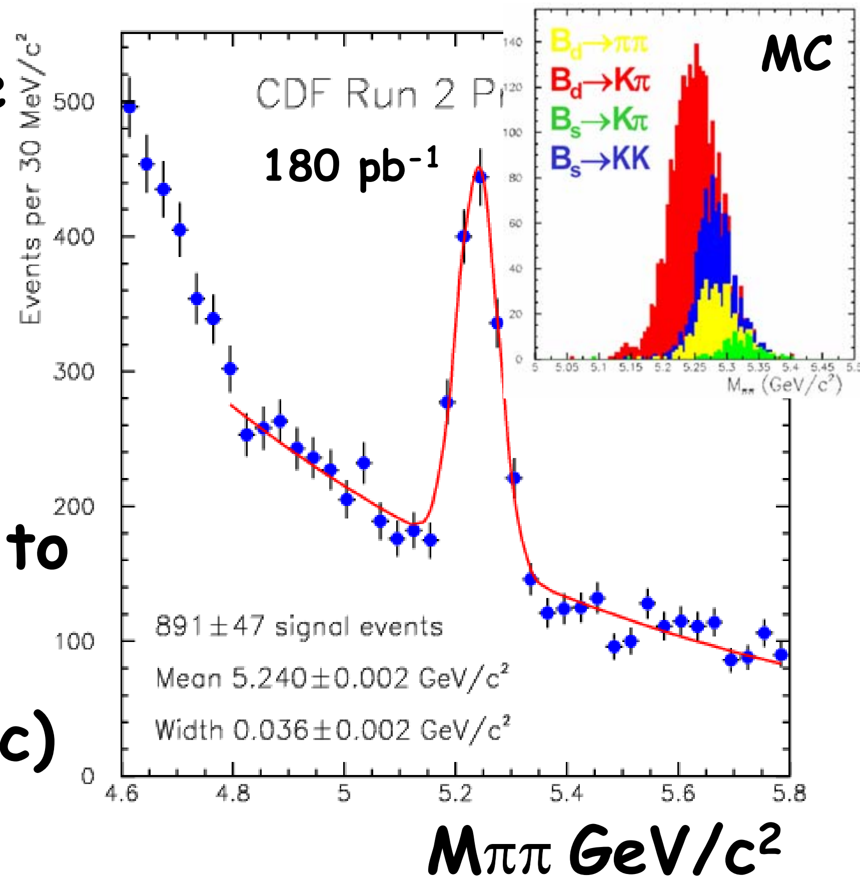
$B^0_d \to K^+ \pi^-$ and c.c.

$B^0_s \to K^+K^-$ and c.c.

$B^0_s \to K^- \pi^+$ and c.c.

Combine kinematics with dE/dx to achieve statistical separation

(TOF doesn't help @p_T >2 GeV/c)



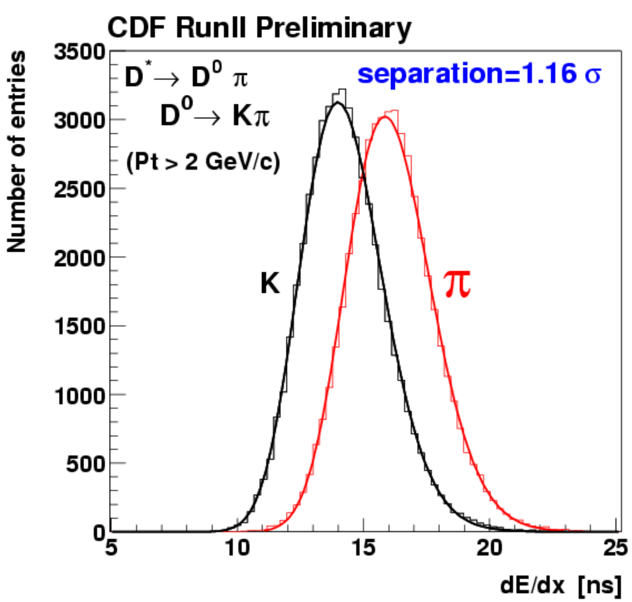
Expect ~ 6500 evts / fb^{-1}

Disentangling signals in $B \to h^+h'^-$

Specific ionization

dE/dx calibrated on 78K D* decays.

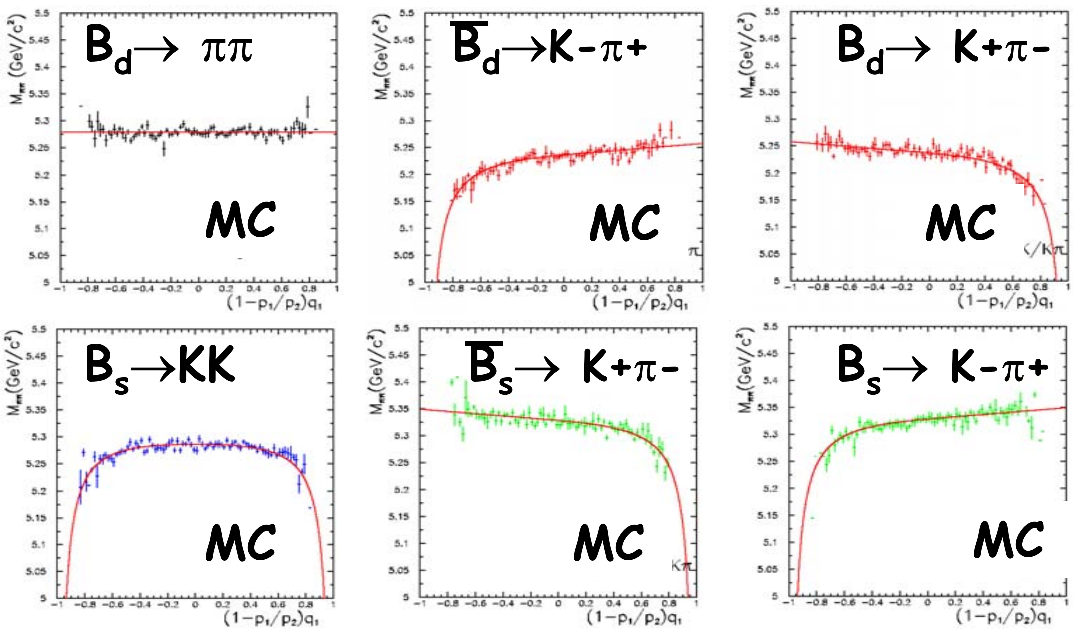
$\pi/K \Rightarrow 1.16\sigma$ (improved to 1.4σ)



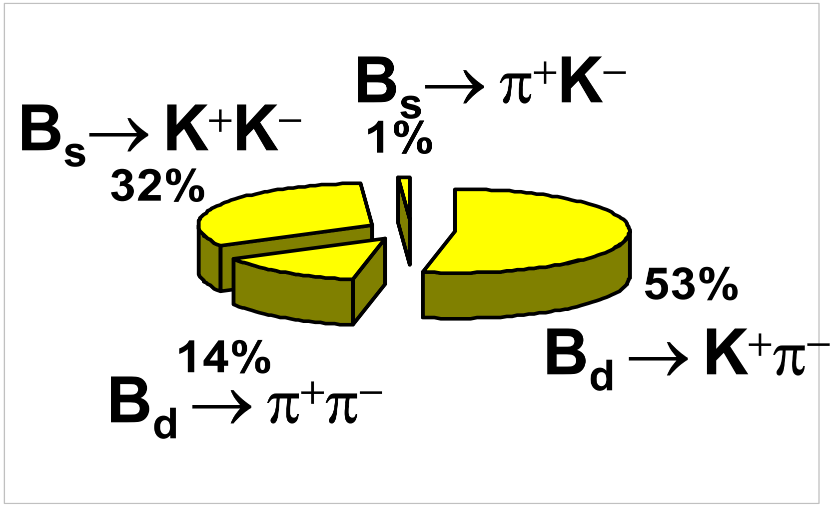
Kinematics

Exploit correlation between mass, charge and momentum imbalance

$M\pi\pi$ vs $(1 - p_{min}/p_{max})Q_{min}$



$B \to h^+h'^-$ results (only 65 pb^{-1})



Measurement of relative fractions not sensitive to $B^0_s \to K^- \pi^+$ yet.

Dominant systematic from dE/dx calibration

$fs \cdot BR(Bs \to KK)/fd \cdot BR(Bd \to K\pi) = 0.74 \pm 0.20(stat) \pm 0.22(syst)$

First evidence of Bs →K+K- decay

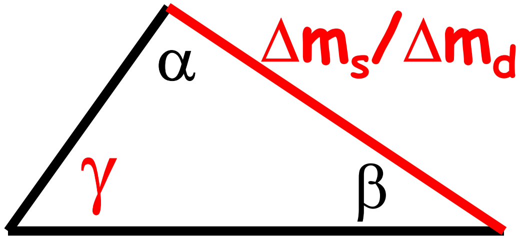
Direct ACP($Bd \to K\pi$) = $0.02 \pm 0.15(stat) \pm 0.02(syst)$

15% statistical error, systematics comparable to B-factories

$BR(Bd \to \pi\pi)/BR(Bd \to K\pi) = 0.26 \pm 0.11(stat) \pm 0.06(syst)$

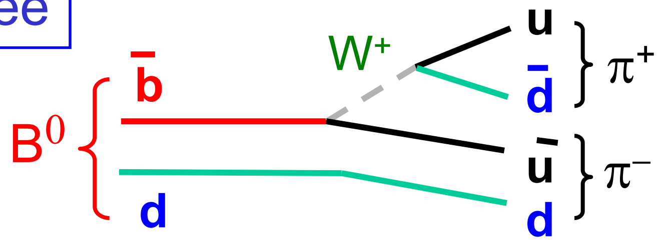
Consistent with B-factories results

Angle γ from $B^0 \to h^+h^-$

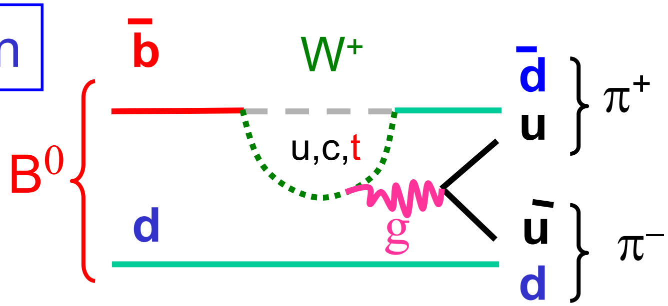


$B^0 \to \pi^+\pi^-$ has two (comparable) decay amplitudes:

Tree



Penguin



direct ~~CP~~ ; ~~CP~~ from mixing alone

$$A_{CP}(t) = A_{CP}^{dir} \cos(\Delta m_d t) + A_{CP}^{mix} \sin(\Delta m_d t)$$

A_{CP}^{dir}, A_{CP}^{mix} functions of γ, β, d, θ $\quad$ ($d\, e^{i\theta} \approx P/T$ decay amplitude)

R. Fleischer ***(PLB 459 (1999) 306):***

Assume U-spin symmetry ($d \leftrightarrow s$)

Similar relation holds for $B_s \to K^+K^-$ (Δm_d replaced by Δm_s)

The 4 asymmetries can be expressed as function of γ, β and P/T.

Parameters can be extracted from fit of $A_{CP}(t)$ for $B_d \to \pi\pi$ and $B_s \to KK$

CPV in other $B \to PV$ and $B \to VV$

Measure direct A_{CP} in $B^+ \to \phi K^+ \to [K^+K^-]K^+$ and c.c.

$$\frac{BR(B^\pm \to \phi K^\pm)}{BR(B^\pm \to J/\psi K^\pm)} = [6.8 \pm 2.1(stat) \pm 0.7(syst)] \cdot 10^{-3}$$

Searching for $B \to VV$

$B^0_s \to \phi\phi$ and c.c. ($\Delta\Gamma_s$ too)

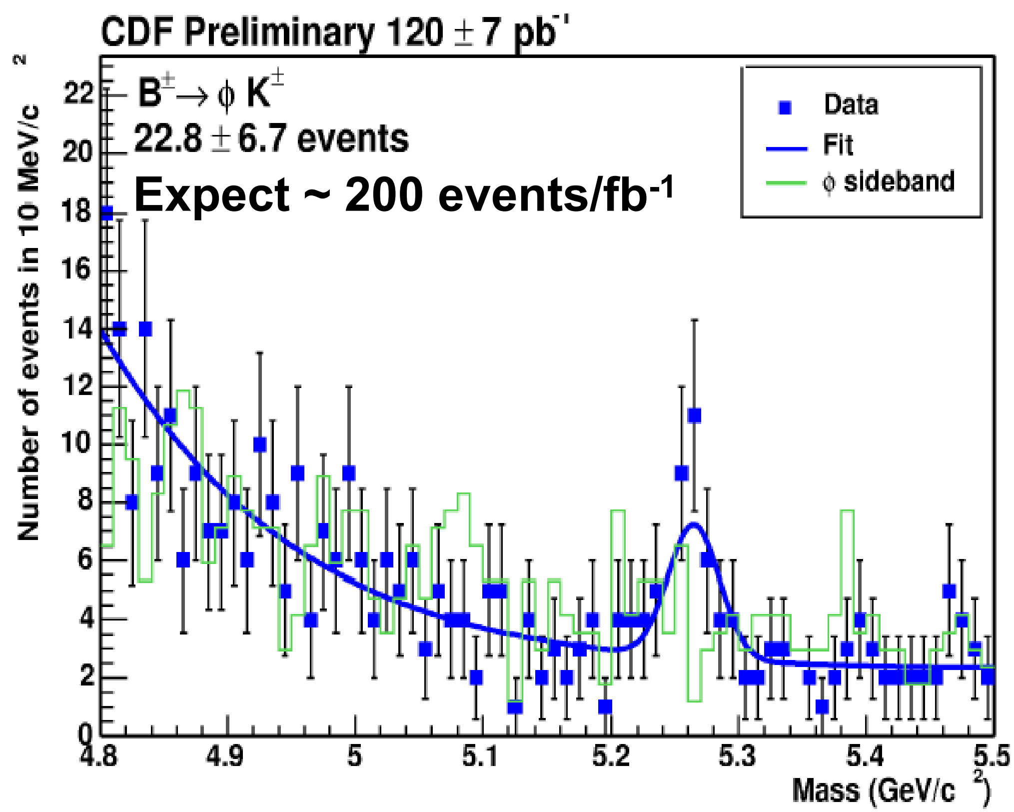
$B^0_d \to \phi K^*$ and c.c.

$B^0_d \to \phi K^0_s$ and c.c.

..and for baryons
(SM expects ~10% CPV)

$\Lambda^0_b \to \phi\Lambda$ and c.c.

$\Lambda^0_b \to pK^-/p\pi^-$ and c.c.

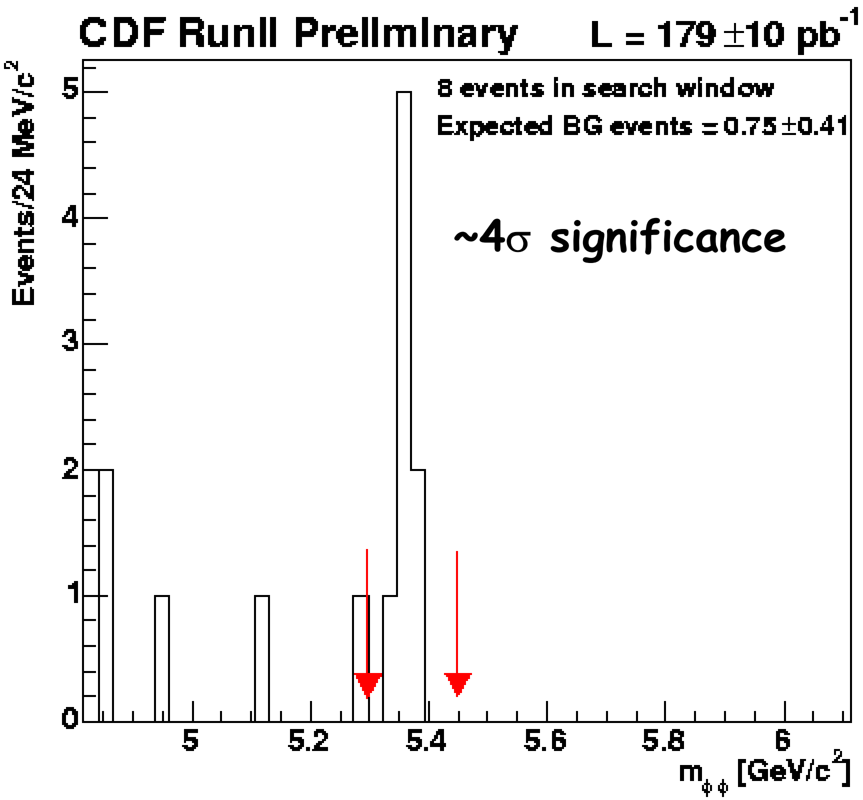


Evidence for $B_s \to \phi\phi$

Angular distributions in $B \to VV$ allow measurement of γ (theoretically clean)

BR measured relative to $B_s \to J/\psi\phi$

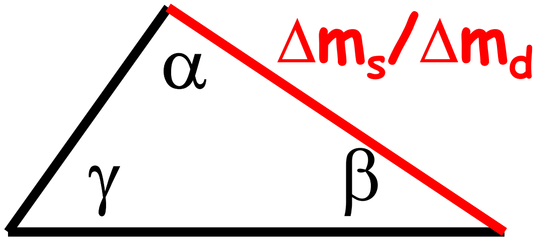
BR = (1.4 ± 0.6 (stat) ± 0.2 (sist.) ± 0.5 (BRs)) × 10^{-5}



Systematic	Error
XFT efficiency by particle species	7.0%
XFT efficiency due to COT ageing	0.3%
other time dependent efficiency	2.4%
Polarization of decay	7.0%
$\Delta\Gamma_s$ theory uncertainty	3.5%
$\psi\phi$ yield determination	6.1%
Backgrounds	3.2%
track–muon stub matching efficiency	5.8%
sub-total	14.2%
BR($\psi\phi$) and daughter BR	36%
Total	38.7%

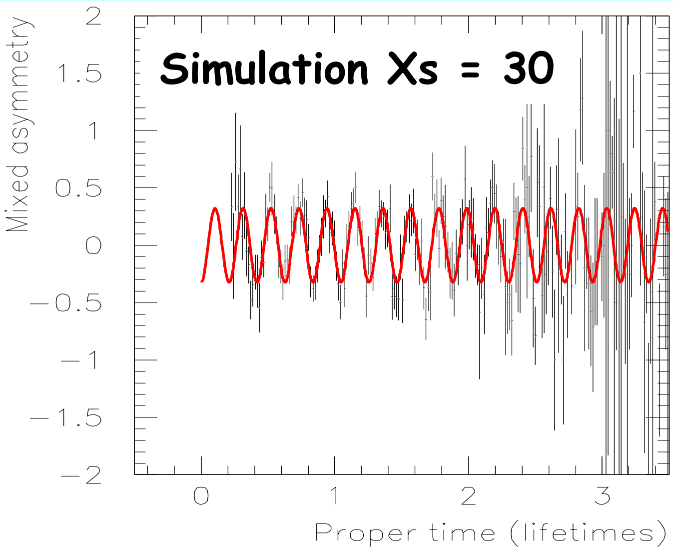
Ingredients for B^0_s mixing

$$A_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = D \cdot \cos(\Delta m_s t)$$



1. **Reconstruct the final state** (use fully rec. $B^0_s \to D^-_s \pi^+(3\pi)$) **with good S/B** (thanks to precise tracking, vertexing, PID)

2. **Measure proper decay time:**



$$c\tau = \frac{L_{xy}}{\gamma\beta} \;;\quad \gamma\beta = P_T(B) / M(B)$$

<u>Current limit</u>:

$\Delta m_s \geq 14.4\ ps^{-1}$

$$\sigma_{c\tau} = \left(\frac{\sigma_L}{\gamma\beta}\right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta}\right) \cdot c\tau$$

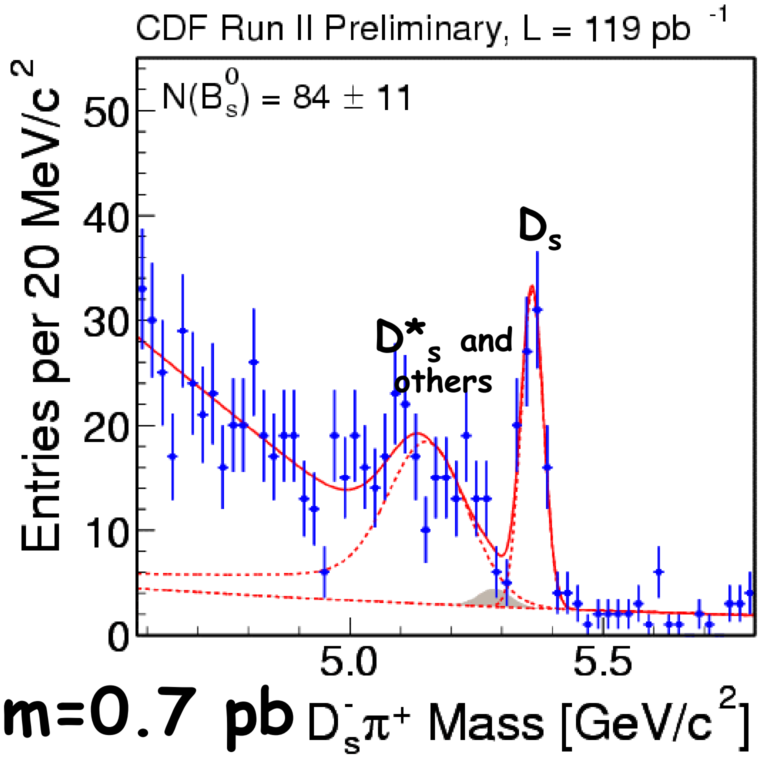
67 fs (SVX II detector)
50 fs (also Layer 00 is used)

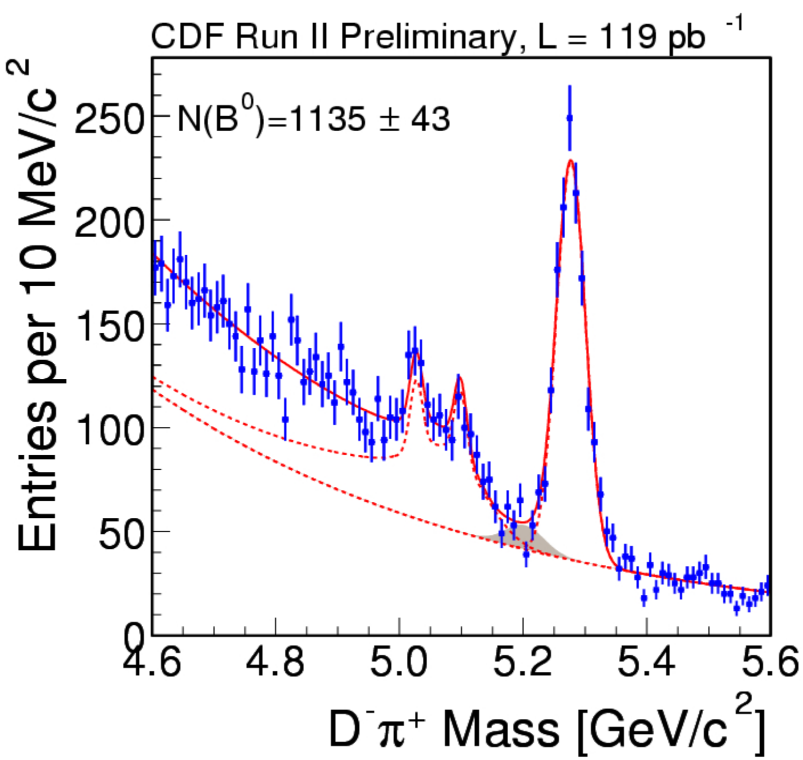
Error on B momentum, ~ 15% (semileptonic)
negligible (~ 0.5%) for fully reconstructed final states

3. **Identify the flavor of B_s at production:** B-flavor tagging algorithms

First steps towards B^0_s mixing

"Golden channel": $B^0_s \to D^-_s \pi^+ \to [\phi\pi^-]\,\pi^+ \to [[K^+K^-]\pi^-]\,\pi^+$
maximum proper time resolution resolves fast oscillations.





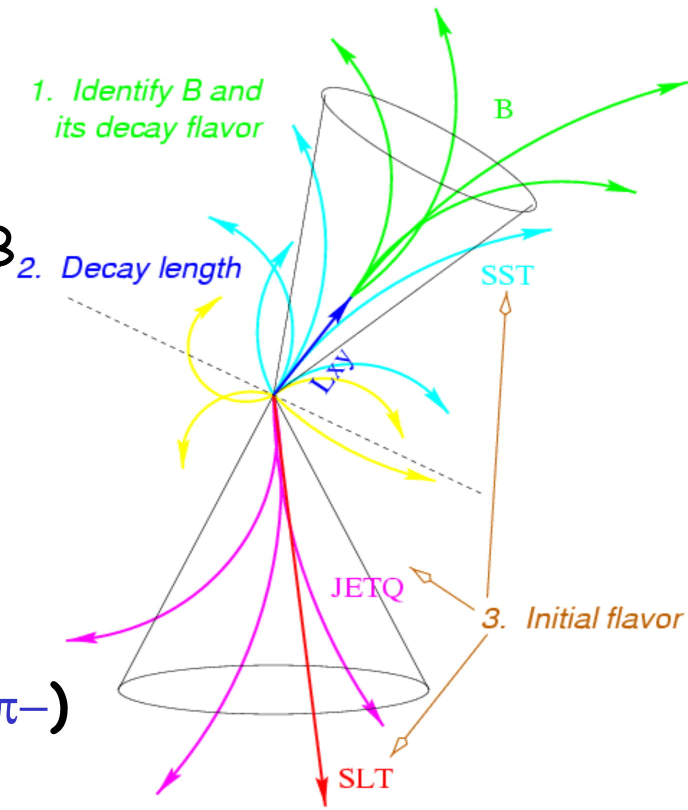
S/B ~ 2

Yield/Lum=0.7 pb

$$\frac{f_s \cdot BR(B^0_s \to D^-_s\pi^+)}{f_d \cdot BR(B^0_d \to D^-\pi^+)} = 0.35 \pm 0.05(stat) \pm 0.04(syst) \pm 0.09(BR)$$

Low statistics: plan to add $B_s \to D_s 3\pi$ and $D_s \to K^*K/K_sK/3\pi$

B Flavor Tagging



OST (opposite side tagging):

B's produced in pairs → tag flavor of opposite B

JETQ: sign of the weighted average charge of opposite B-Jet

SLT: identify the soft lepton from semileptonic decay of opposite B

SST (same side tagging):

$\overline{B}^0$ (B^0) is likely to be accompanied by a $\pi+$ ($\pi-$)

Search for the track with minimum P_T^{REL}

Kaon taggers (new in CDF):

OST (K from b→c→s transition)

SST (K from fragmentation)

CDF tagger	εD^2
Soft muon	0.7 ± 0.1 %
Soft electron	in progress
Jet charge	in progress
Same side	2.4 ± 1.2 %
Kaon	in progress

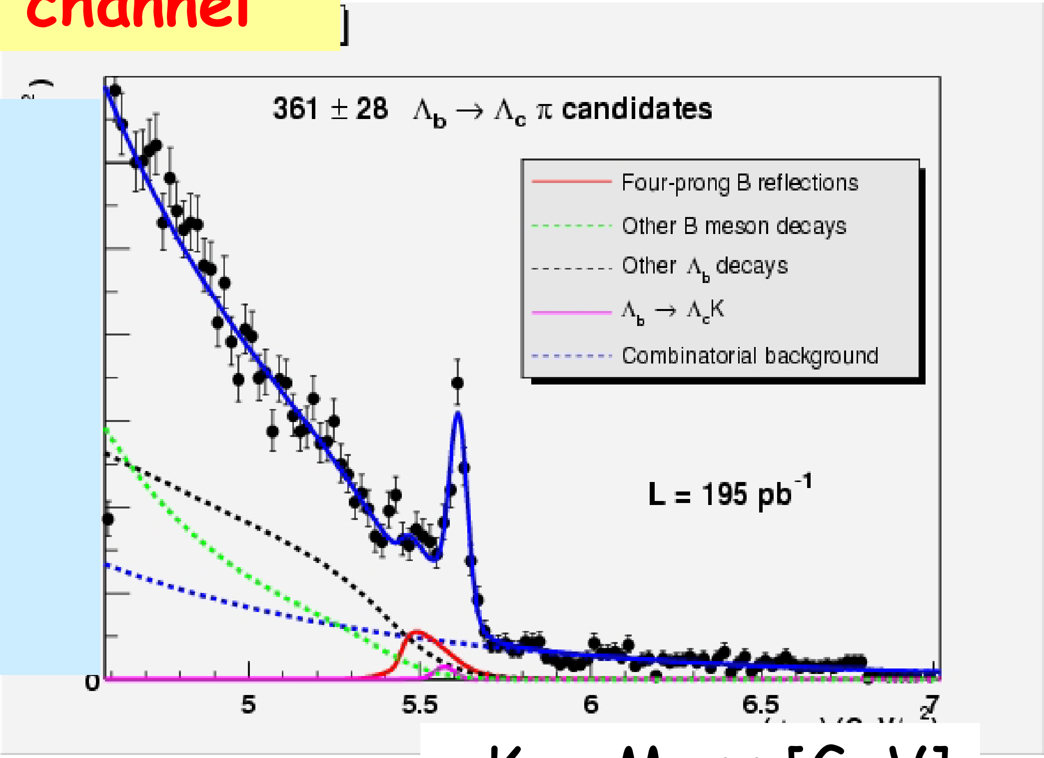
Hadronic $\Lambda_b \to \Lambda_c\ \pi$ signal

$\Lambda_b \to \Lambda_c\ \pi \to [pK\pi]\ \pi$

Largest fully rec. hadronic channel

- Measure mass, lifetime, polarization
- Precise Lifetime $\to \dfrac{\tau(\Lambda_b)}{\tau(B^0)}$

Discrepancy with theory:
Is it valid for baryons ?



pKππ Mass [GeV]

$f\Lambda_b \cdot BR(\Lambda_b \to \Lambda_c \pi)/fd \cdot BR(Bd \to D\pi) = 0.66 \pm 0.11(stat) \pm 0.09(syst)\ ) \pm 0.18(BR)$

Cabibbo-suppressed decays of D^0

Cabibbo suppressed D^0 decays seen in mass plot.

$\Gamma(D^0 \rightarrow KK)/\Gamma(D^0 \rightarrow K\pi)=9.96\pm0.11\pm0.12\%$

$\Gamma(D^0 \rightarrow \pi\pi)/\Gamma(D^0 \rightarrow K\pi)=3.608\pm0.054\pm0.040\%$

compare with FOCUS (2003)

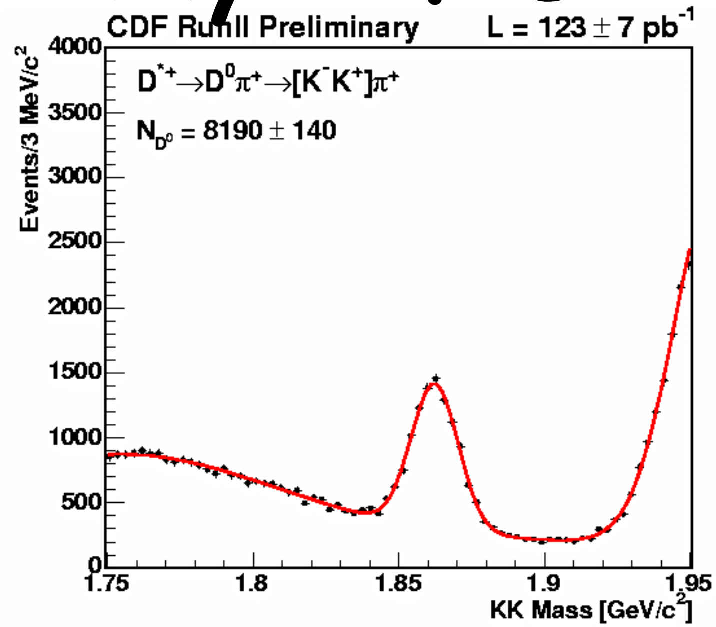
$\Gamma(D^0 \rightarrow KK)/\Gamma(D^0 \rightarrow K\pi) = 9.93\pm0.14\pm0.14\%$

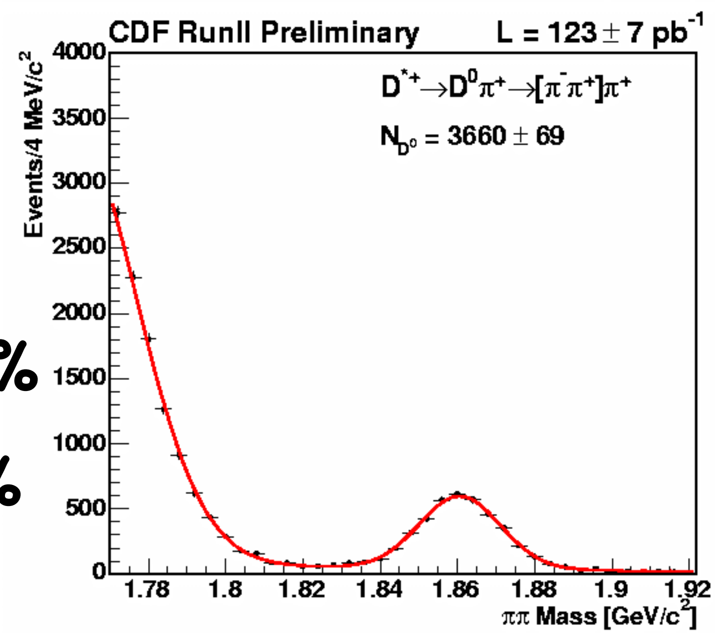
$\Gamma(D^0 \rightarrow \pi\pi)/\Gamma(D^0 \rightarrow K\pi) = 3.53\pm0.12\pm0.06\%$

CP asymmetry: tagging the soft π with D* decays.

$A(D^0 \rightarrow KK)=2.0\pm1.2(stat)\pm0.6(syst)\ \%$

$A(D^0 \rightarrow \pi\pi)=3.0\pm1.3(stat)\pm0.6(syst)\ \%$





FCNC with $D^0 \to \mu\mu$ decays

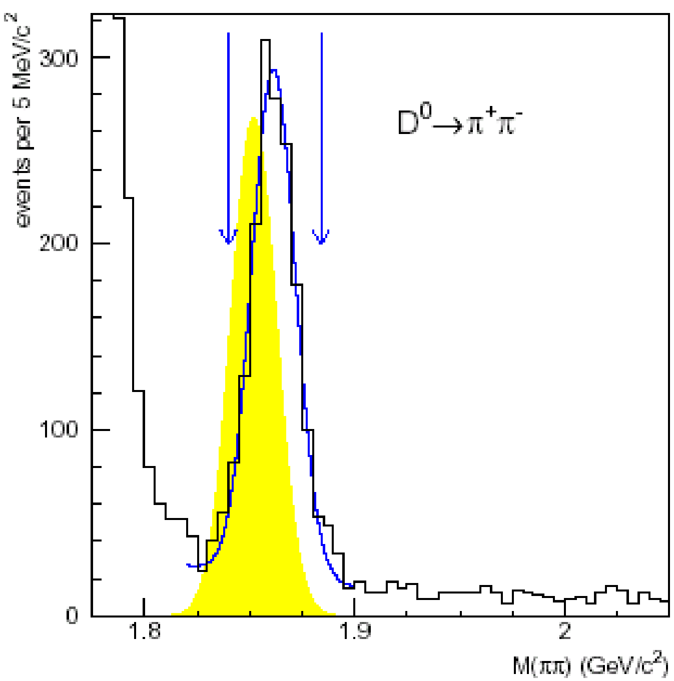
SM BR is 3×10^{-13}, can grow by 10^7 in R-violating SUSY

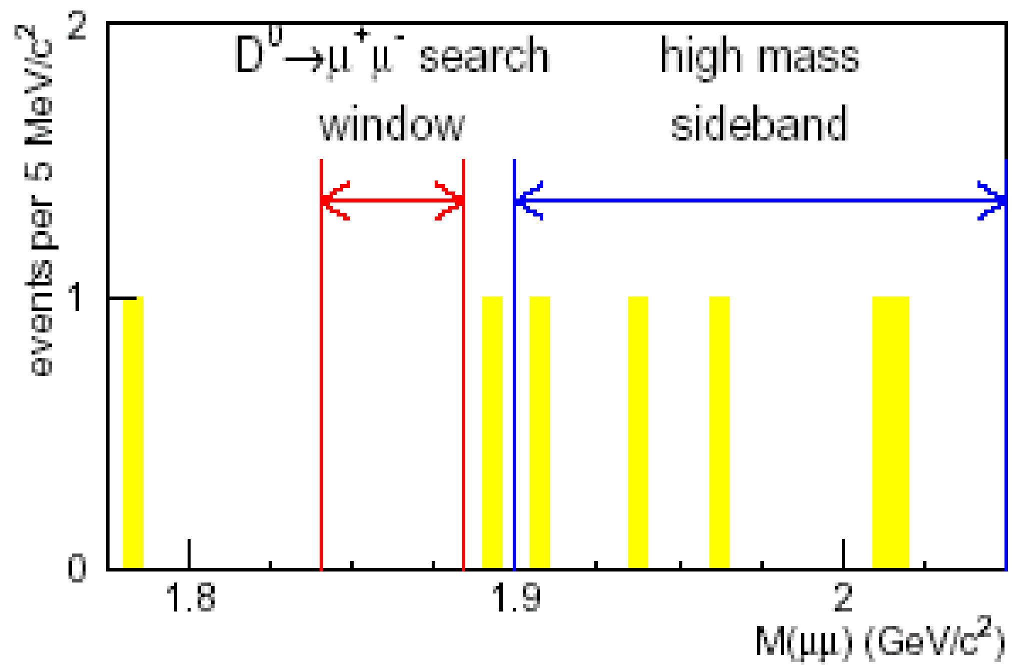
D0 $\to$ $\pi\pi$ used as reference sample

0 events observed, 1.6 ± 0.7 estimated from BG

$BR(D^0 \to \mu\mu) < 2.5\ (3.3) \times 10^{-6}$ at 90% (95%) CL

(improves PDG by a factor 2)





Conclusions

The upgraded CDF detector is taking new data

Great B physics potential, we have results on:

- Masses, lifetimes in the $B \to J/\psi K$ exclusive channels and production cross sections
- New impact parameter trigger: huge and clean semileptonic/all hadronic B signals (also Charm):
  - Large and clean $B \to lDX$ signals reconstructed (excellent for lifetime, tagging and Δm_d meas.)
  - $B^0 \to h^+h^-$: important results on our way to γ ($B^0_s \to KK$, CP in $B^0_d \to K\pi$)
  - $B^0_s \to D^-_s \pi^+$: first ingredients towards Δm_s

Lots of Beauty (and Charm) at the Tevatron