Studies of B states at the Tevatron

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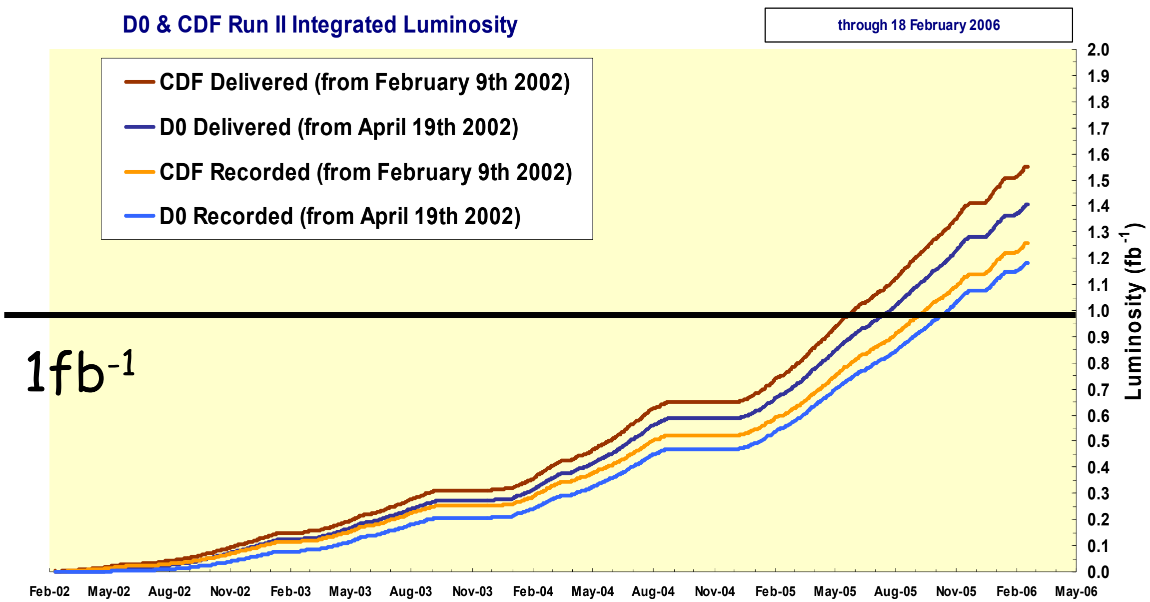
Outline

- Introduction
  - Tevatron status
  - Detectors

- Too many results to discuss so focus on new results which are not accessible at B factories
  - B**
  - Λ_b
  - B_c
  - $B_s \rightarrow KK$
  - Dimuon Asymmetry

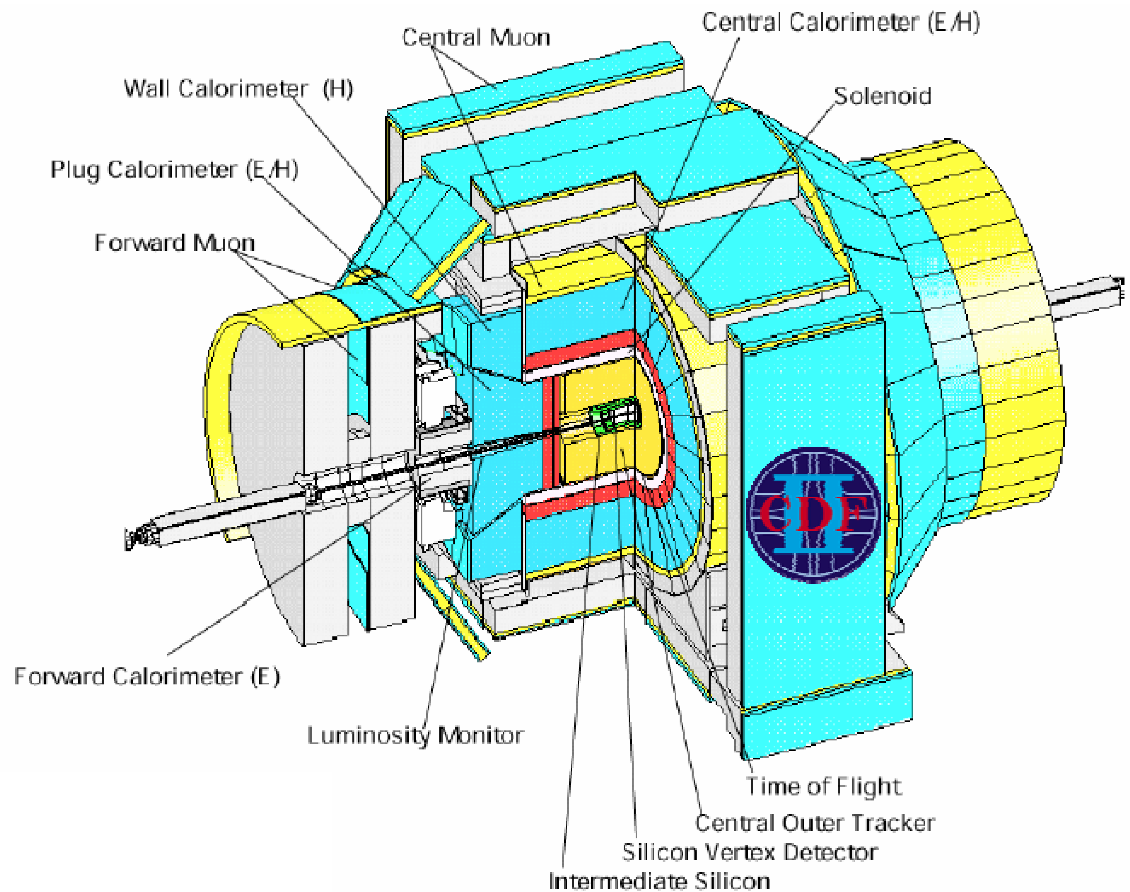
Tevatron performance

- Excellent performance of Tevatron in 2004 and 2005
- Machine delivered more than 1,500 pb^{-1}
- recorded (DØ/CDF)
  - 1.2 pb^{-1} / 1.4 pb^{-1}
  - high data taking efficiency ~85%
  - record luminosity of 1.7×10^{32} cm^{-2}/s in January 2006
- Current datasets analyzed
  - Up to 1000 pb^{-1} analyzed
  - compare with ~100 pb^{-1} Run I



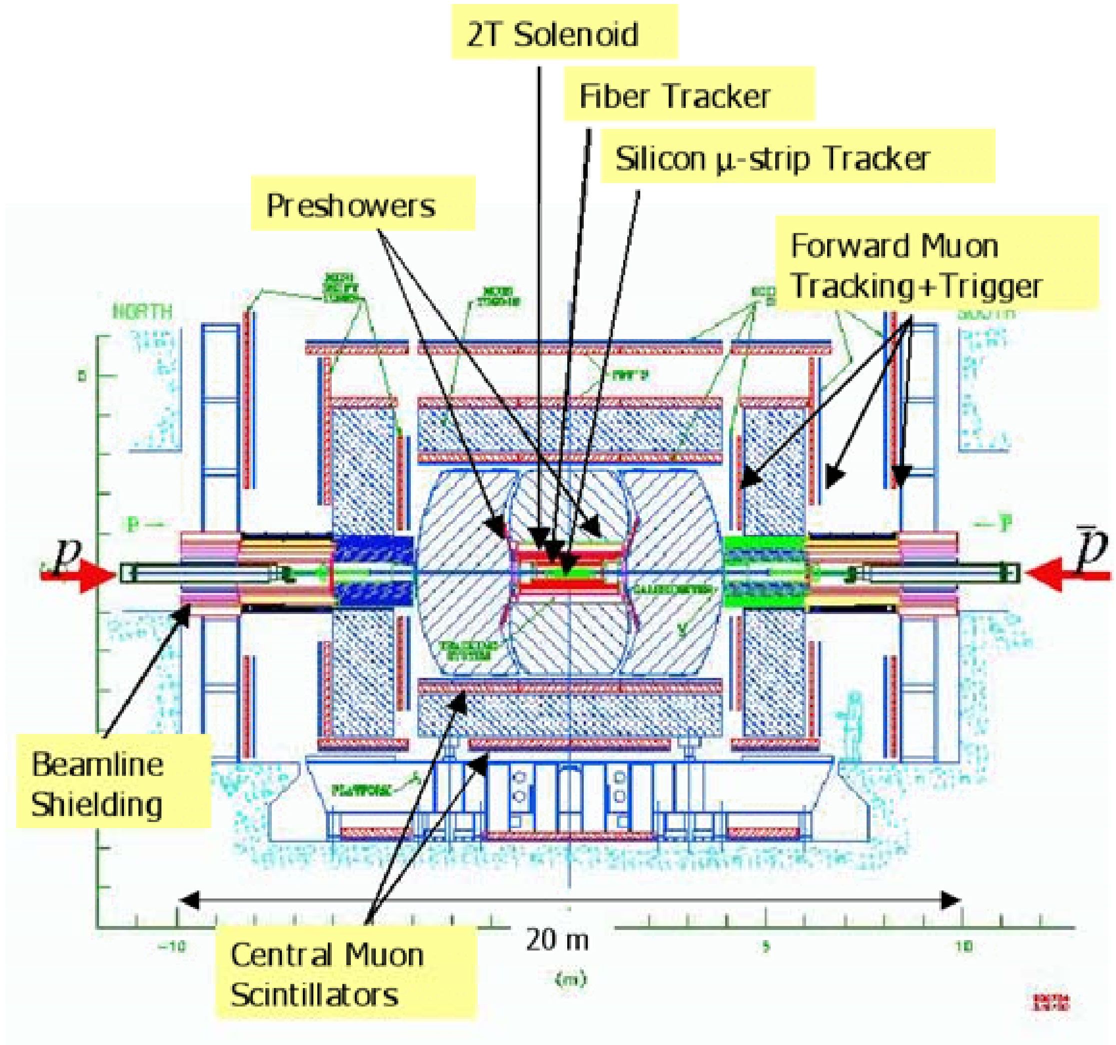
CDF detector

- Solenoid 1.4T
- Silicon Tracker SVX
  - up to $|\eta|<2.0$
  - SVX fast r-ϕ readout for trigger
- Drift Chamber
  - 96 layers in $|\eta|<1$
  - particle ID with dE/dx
  - r-ϕ readout for trigger
- Time of Flight
  - $\rightarrow$particle ID



DØ detector

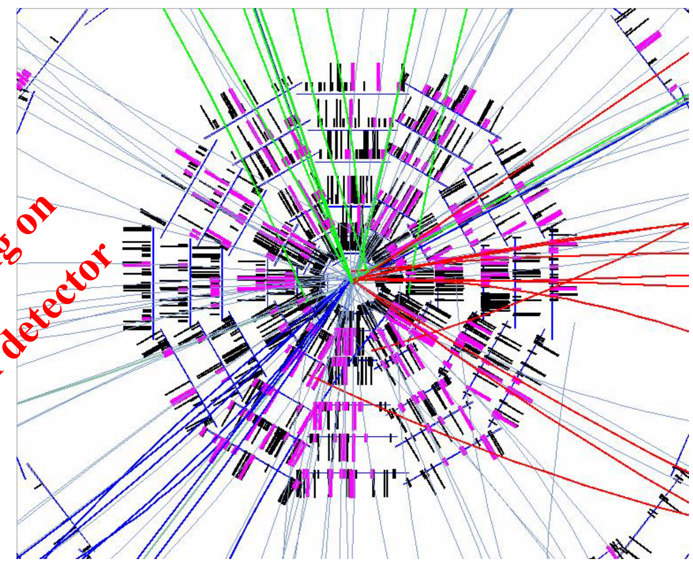
- 2T Solenoid
- forward Muon + Central Muon detectors
  - excellent coverage $|\eta|<2$
- Fiber Tracker
  - 8 double layers
- Silicon Detector
  - up to $|\eta|\sim3$



B production at Tevatron

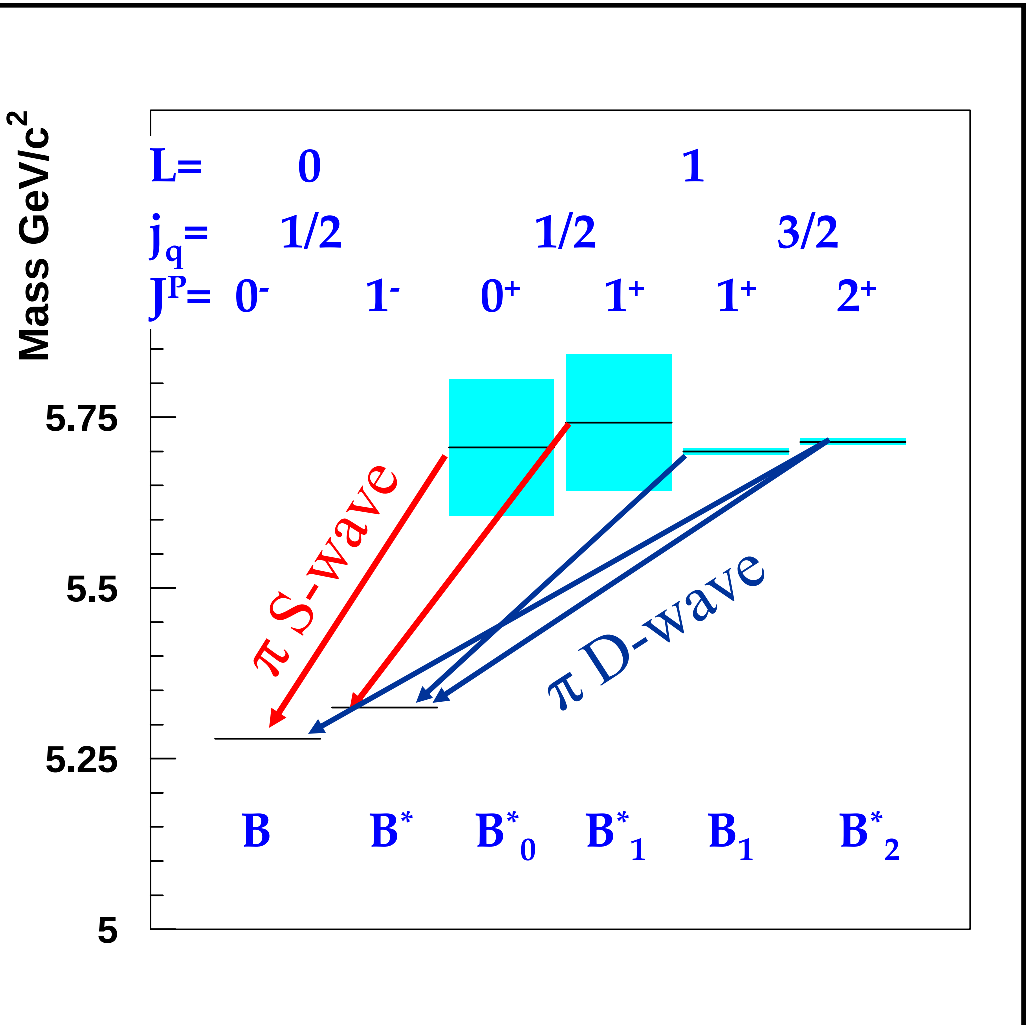
- Pro's:
  - large cross section >10[4] x larger than at present B-factories $\Upsilon(4S)$
  - all kinds of b hadrons produced:
    - B_d, B_s, B_c, B^{**}, Λ_b, Ξ_b, …
- Con's:
  - QCD background overwhelming
  - efficient trigger and reliable tracking necessary
  - soft p_t spectrum, smaller boost than LEP
- Key for B physics program:
  - Muon system
  - Muon trigger (single and dimuon triggers)
  - Silicon Vertex + Tracker
  - trigger on displaced vertices/tracks

$$\sigma(p\bar{p} \rightarrow b\bar{b}) \approx 150\,\mu b$$
$$@\sqrt{s} = 2\text{TeV}$$



Lots going on in Si detector

B** or B_J $(b\bar{q})$ system theory



Good qualitative understanding

- **4 *P*-states: B^*_0, B^*_1, B_1, B^*_2**
- **B^*_0, B^*_1 decay through S-wave They are very wide (~100 MeV).**
- **B_1, B^*_2 decay through D-wave and should be narrow (~10 MeV)**
- **B^*_2 can decay to $B^*\pi$ and $B\pi$;**
- **B_1 can decay only to $B^*\pi$;**

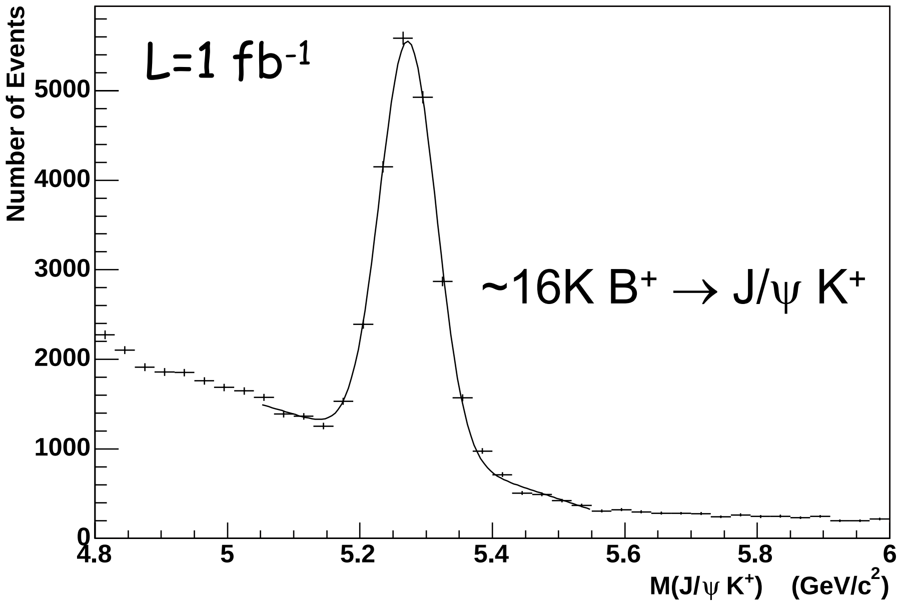
Less good quantitative description

- **Prediction of masses, widths and decay properties is less precise and depends on many model parameters**

Analysis

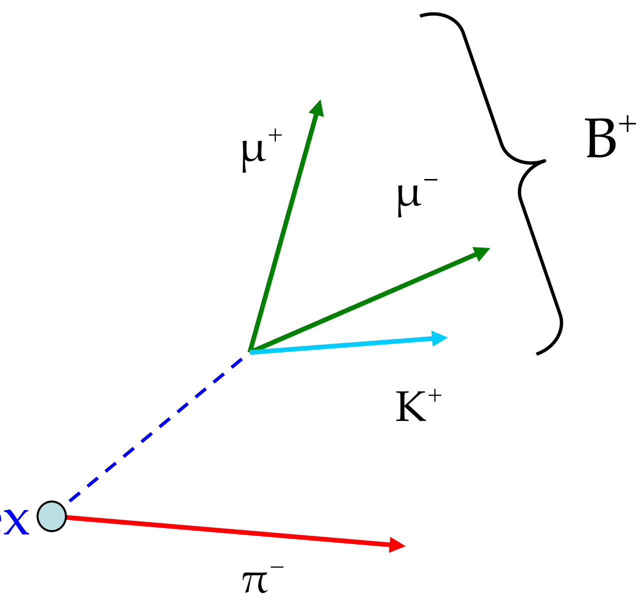
- Search for narrow states decaying to $B^{+(*)}\pi$
  - $B_1 \to B^{*+}\pi^-$; $B^{*+} \to B^+\gamma$
  - $B_2^* \to B^{*+}\pi^-$; $B^{*+} \to B^+\gamma$
  - $B_2^* \to B^+\pi^-$
- Reconstruct $B^+ \to J/\psi\ K^+$ with $J/\psi \to \mu\mu$

D0 RunII preliminary



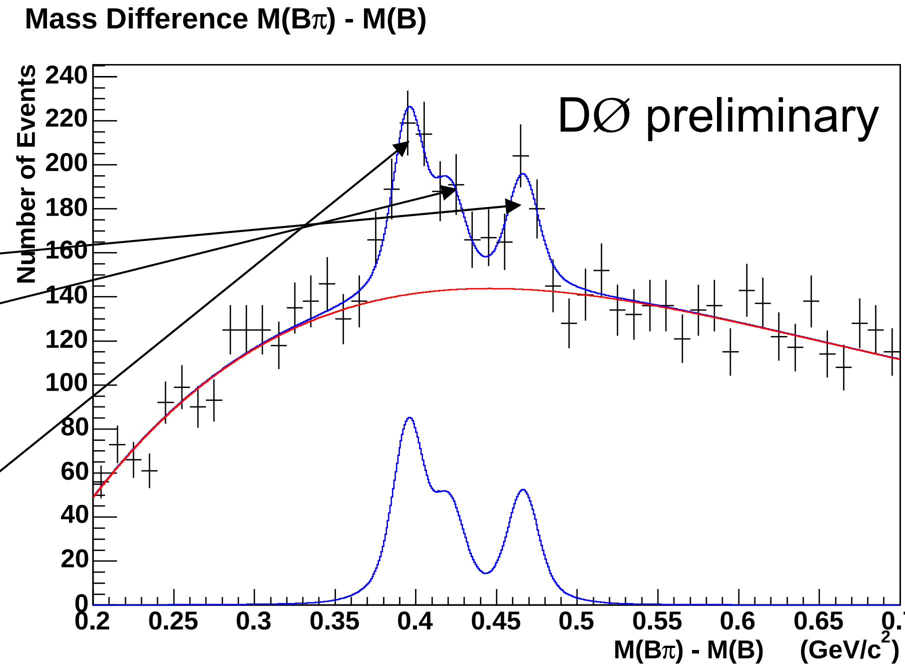
B_J selection

- For each B hadron an additional track with
  - $P_T > 0.75$ GeV
  - Correct charge correlation ($B^+\pi^-$ or $B^-\pi^+$)
  - Since B_J decays immediately after production, track was required to originate from primary vertex.



B_J

L=1 fb^{-1}



- Form mass difference $\Delta M = M(B\pi) - M(B)$
- 3 peak structure
  - 1 peak direct decay $B_2^* \to B^+\pi$
  - $B_2^* \to B^{+*}\pi$ with $B^{+*} \to B^+\gamma$ (γ has energy of 45.78 ± 0.35 MeV) since γ is not reconstructed, we expect a peak separated from direct peak by γ energy
  - $B_1 \to B^{+*}\pi$ (mass peak shifted down by photon energy) (Note $B_1 \to B\pi$ is forbidden by angular momentum and parity conservation)

Models predict widths of B_1 and B_2^* to be similar so they are set equal in fit

$M(B_1)$=5720.8 ± 2.5(stat) ± 5.3 (sys) MeV $M(B_2^*)-M(B_1)$= 25.2 ± 3.0(stat) ± 1.1 (sys) MeV

$\Gamma_1=\Gamma_2$= 6.6 ± 5.3(stat) ± 4.2 (sys) MeV

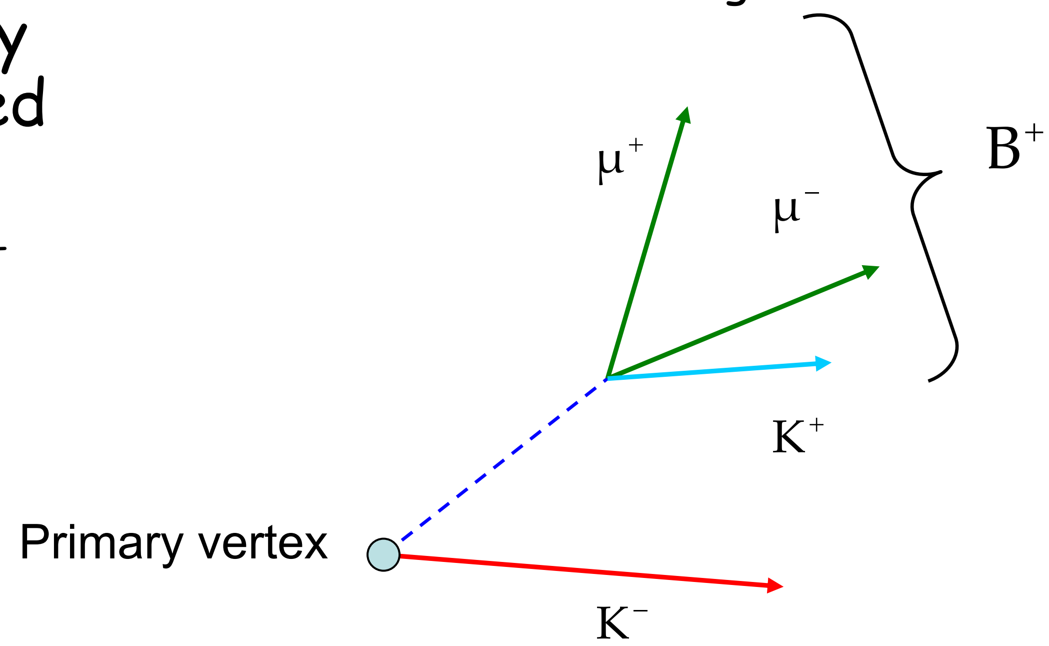
- $\dfrac{BR(B_2^* \to B^*\pi)}{BR(B_2^* \to B^{(*)}\pi)} =$ 0.513 ± 0.092(stat) ± 0.115(sys)
- $\dfrac{BR(B_1 \to B^{*+}\pi)}{BR(B_J \to B^{(*)}\pi)} =$ 0.545 ± 0.64(stat) ± 0.071 (sys)
- $\dfrac{BR(b \to B_J^0 \to B\pi)}{BR(b \to B^+)} =$ 0.165 ± 0.024 (stat) ± 0.028 (sys)

First measurement of production rate, world's best mass measurement.

Search for B^*_{s2}

- Similar to B**, quark model predicts two wide (B^*_{s0} and B^*_{s1}) and two narrow (B_{s1} and B^*_{s2}) bound P states in $b\bar{s}$ system
- Due to Isospin conservation, the decay to $B_s\pi$ highly suppressed
- Search for excited states decaying to B^+K^-
- Similar to B** search

- For each B hadron an additional track
  - $P_T > 0.6$ GeV
  - Charge opposite to charge of B^+
  - Track was required to originate from primary vertex
  - Kaon mass assigned to track



Results

1 fb^{-1}

Mass difference $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$

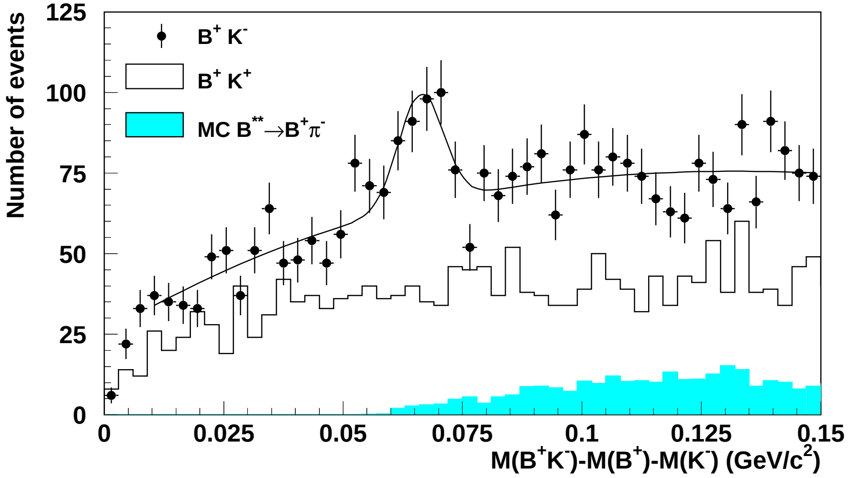
Significance of signal > 5.

First Direct observation of B^*_{s2}

Wrong sign charge correlations shows no evidence of a peak

MC B** decaying to $B^{(*)}\pi$ but reconstructed as B^+K^- show no evidence of a peak.

D0 RunII preliminary



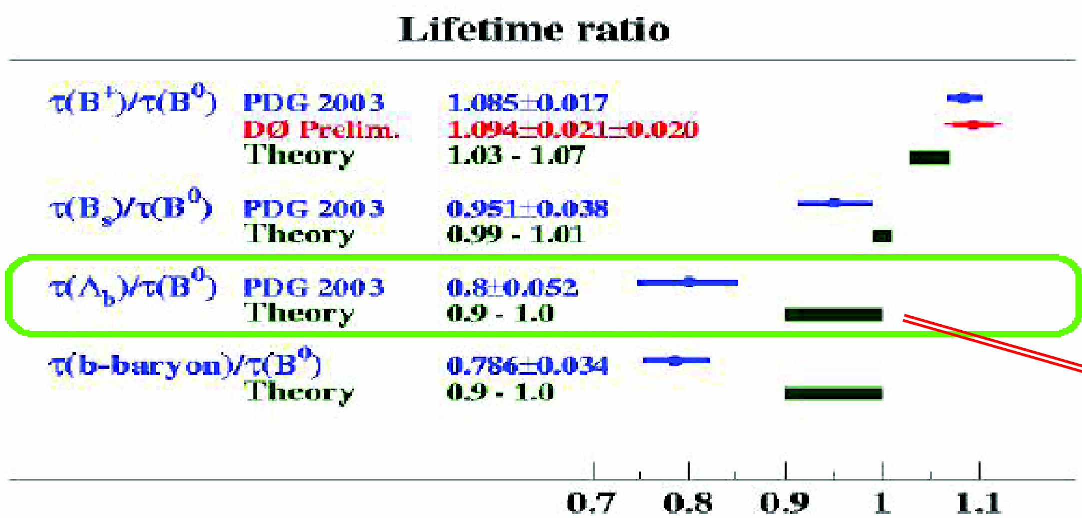
- $M(B^*_{s2}) = 5839.1 \pm 1.3$ MeV

- Note: B_{s1} can only decay to $B^{*+}K^-$, the theory predicts the same mass splitting: $M(B_2^*) - M(B_1) = 25.2 \pm 3.2$ MeV, then B_{s1} decaying to $B^{*+}K^-$ is forbidden since $M(B_{s1}) < M(B^{*+}) + M(K^-)$. Decay of $B^*_{s2} \rightarrow B^{*+}K^-$ would produce a signal at ~ 20 MeV, however due to such a small mass difference and the additional suppression factor due to the orbital angular momentum L=2 result in a strong suppression of this decay,

Λ_b

- Lightest b baryon (udb)
- Rich physics program in the Λ_b
  - Spin role in heavy hyperons (polarization)
  - CP violation
  - T violation ($\Lambda_b \to \Lambda l^+ l^-$)
  - New physics ($\Lambda_b \to \Lambda l^+ l^-$)
  - Testing HQE theory in b baryons (lifetime)

Lifetime



Status as a few years ago.

A lot of theoretical work

Lifetime ratio	Measured value	Predicted range
$\tau(B^+)/\tau(B^0)$	1.076 ± 0.008	$1.04 - 1.08$
$\bar{\tau}(B_s^0)/\tau(B^0)^a$	0.920 ± 0.030	$0.99 - 1.01$
$\tau(\Lambda_b^0)/\tau(B^0)$	0.806 ± 0.047 (*)	$0.81 - 0.91$
$\tau(b\text{-baryon})/\tau(B^0)$	0.792 ± 0.032	$0.81 - 0.91$

[a] Using $\bar{\tau}(B_s^0) = 1/\Gamma_s = 2/(\Gamma_L + \Gamma_H)$.

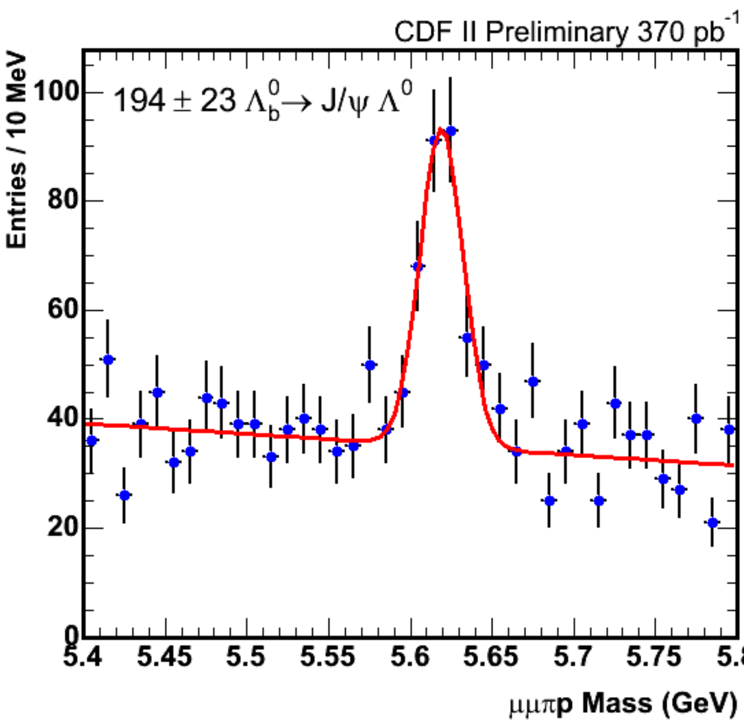
(*) Includes D0 and CDF Run II measurements

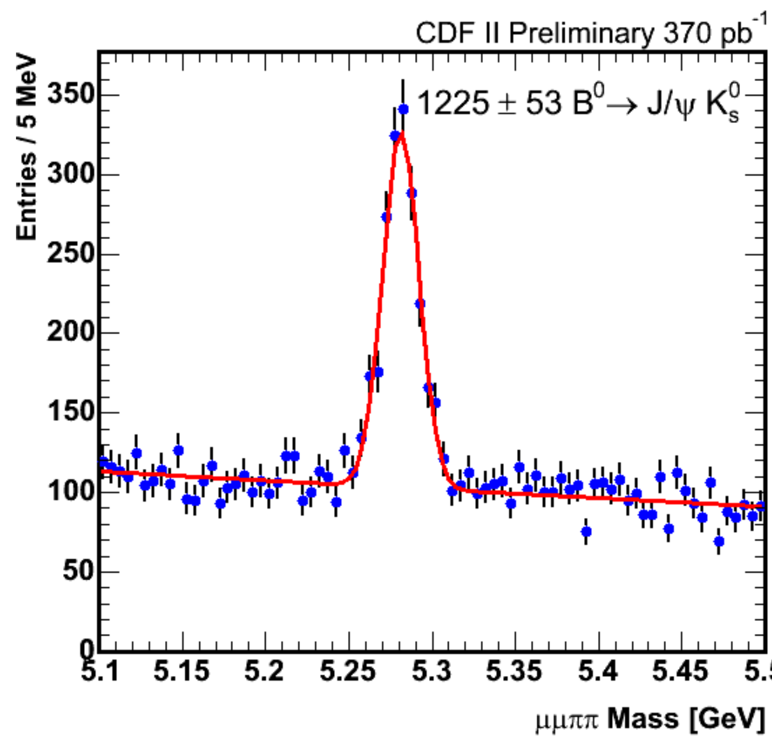
Λ_b

- Reconstruct both $\Lambda_b \to J/\psi\ \Lambda$ with $\Lambda \to p\pi$ and $B_d \to J/\psi\ K_s$. Similar event topologies and can use the much larger yields in $B_d \to J/\psi\ K_s$ to validate analysis procedure and study systematics

Blind analysis to avoid biases

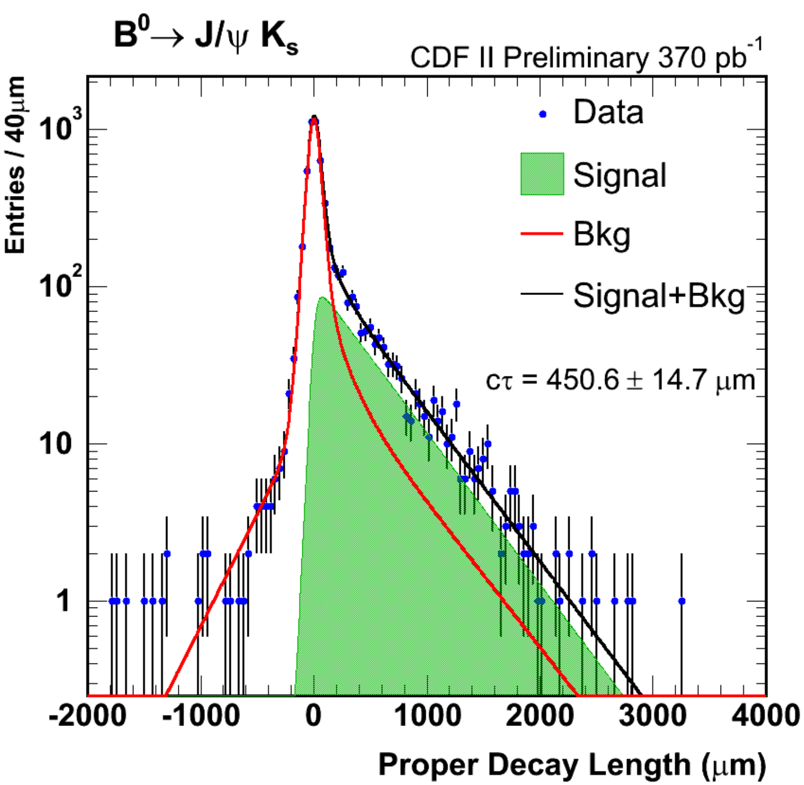
Measured lifetime of over 8 different B^0 and B^+ decays to ensure lifetime measurements well understood

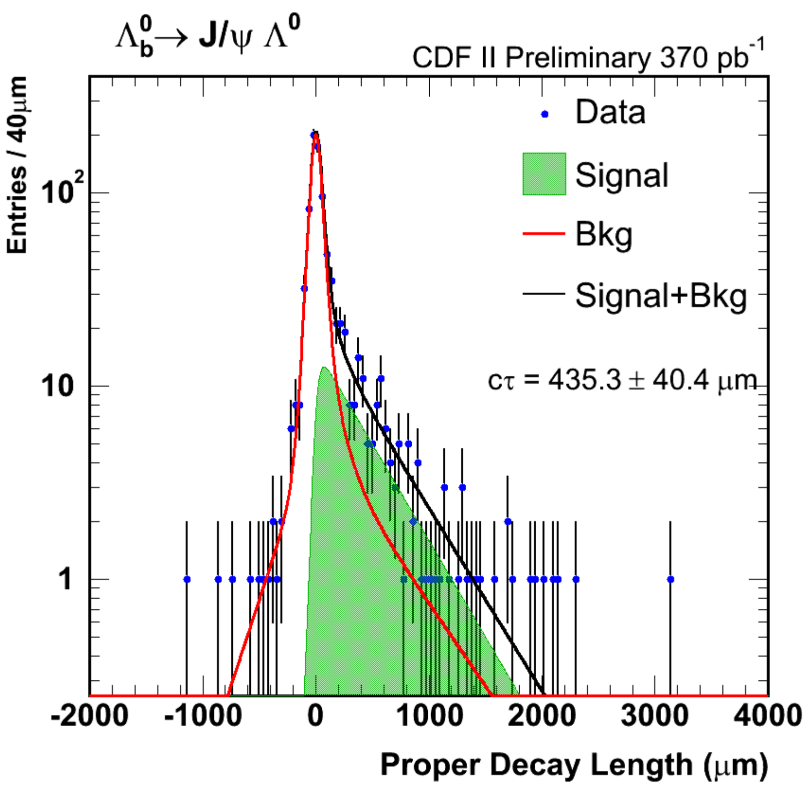




Results

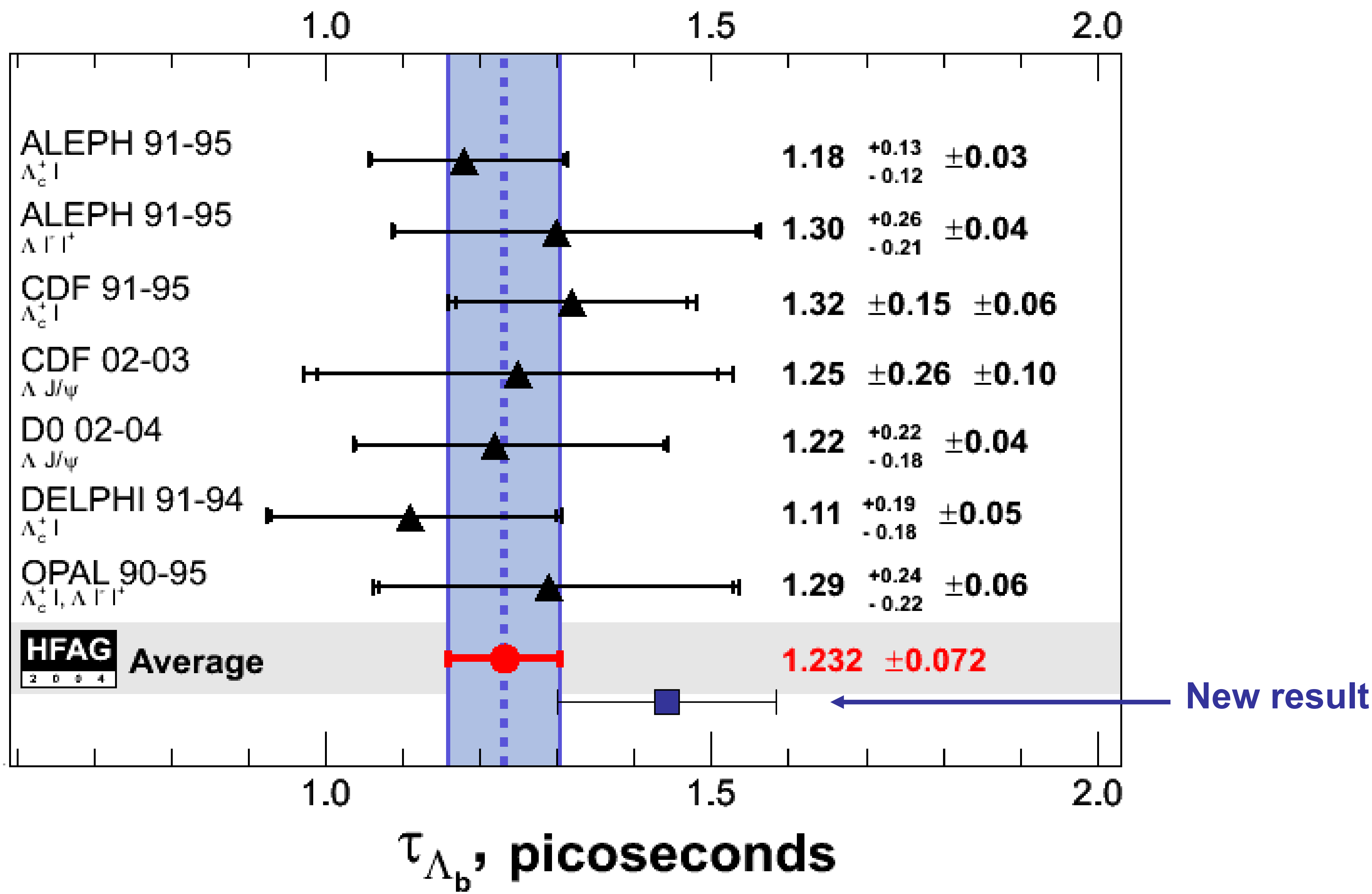
- Extract lifetime with unbinned likelihood fit to proper decay length and mass event information.





$\tau(B^0)$=1.503 + 0.050 – 0.048 ± 0.016(sys) ps
PDG: $\tau(B^0)$=1.536 ± 0.014 ps

$\tau(\Lambda_b)$=1.45 + 0.14 – 0.13 ± 0.02 (sys) ps
$\tau(\Lambda_b)/\tau(B^0)$ = 0.944 ± 0.089



1.0
1.5
2.0
ALEPH 91-95
$\Lambda_c^+ l$
1.18 +0.13 -0.12 ±0.03
ALEPH 91-95
$\Lambda l^- l^+$
1.30 +0.26 -0.21 ±0.04
CDF 91-95
$\Lambda_c^+ l$
1.32 ±0.15 ±0.06
CDF 02-03
$\Lambda J/\psi$
1.25 ±0.26 ±0.10
D0 02-04
$\Lambda J/\psi$
1.22 +0.22 -0.18 ±0.04
DELPHI 91-94
$\Lambda_c^+ l$
1.11 +0.19 -0.18 ±0.05
OPAL 90-95
$\Lambda_c^+ l, \Lambda l^- l^+$
1.29 +0.24 -0.22 ±0.06
HFAG 2004
Average
1.232 ±0.072
New result
τ_{Λ_b}, picoseconds

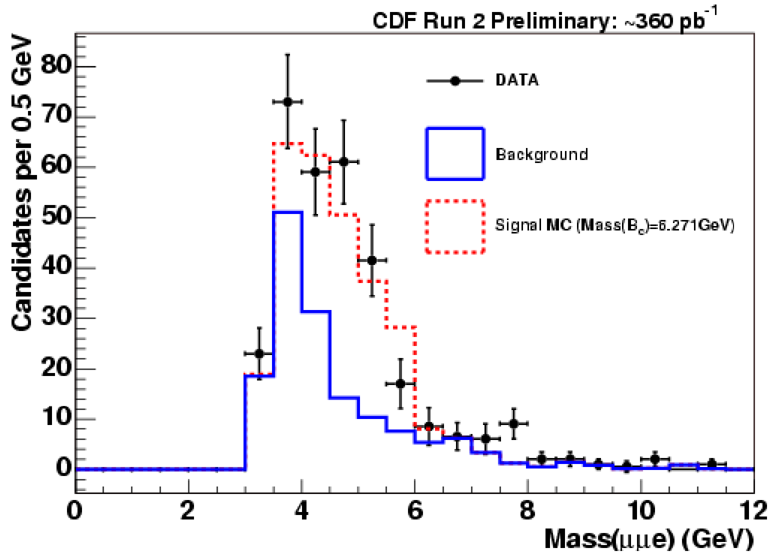
B_c

- B_c is ground state of $b\bar{c}$ system
  - Unique system with two heavy quarks of different flavor
  - Probes heavy-quark theories in the region between the cc and bb
  - m_{exp} = 6400 ± 390 ± 130 MeV/c^2 (first observation $B_c \rightarrow J/\psi\mu X$ CDF Run I, PRD 58, 112004)
  - DØ observed B_c in this mode in 2004
  - m_{exp} = 6287.0 ± 4.8 Mev/c^2 (CDF Run II, $B_c \rightarrow J/\psi\pi$)
  - $\tau_{exp}=0.46^{+0.18}_{-0.18} \pm 0.03$ps (DØ/CDF semileptonic decays)

- B_c challenging. Low production rate
  B^+,B^0:40%, B_s,B baryons: 10%
  B_c~ .05%
- Factor of 3 shorter lifetime so cannot apply long lifetime cuts to reduce backgrounds
- Want to measure properties of B_c
  - Lifetime and Mass measurement
- Precise lifetime measurement will determine the relative importance of the three dominant decay modes and the interactions of the two heavy quarks.

B_c lifetime and production cross section

- Reconstruct $B_c \rightarrow J/\psi e\nu$
- Important to understand backgrounds
  - Fake electrons
  - Electrons from photon conversions
  - $b\bar{b}$ contamination



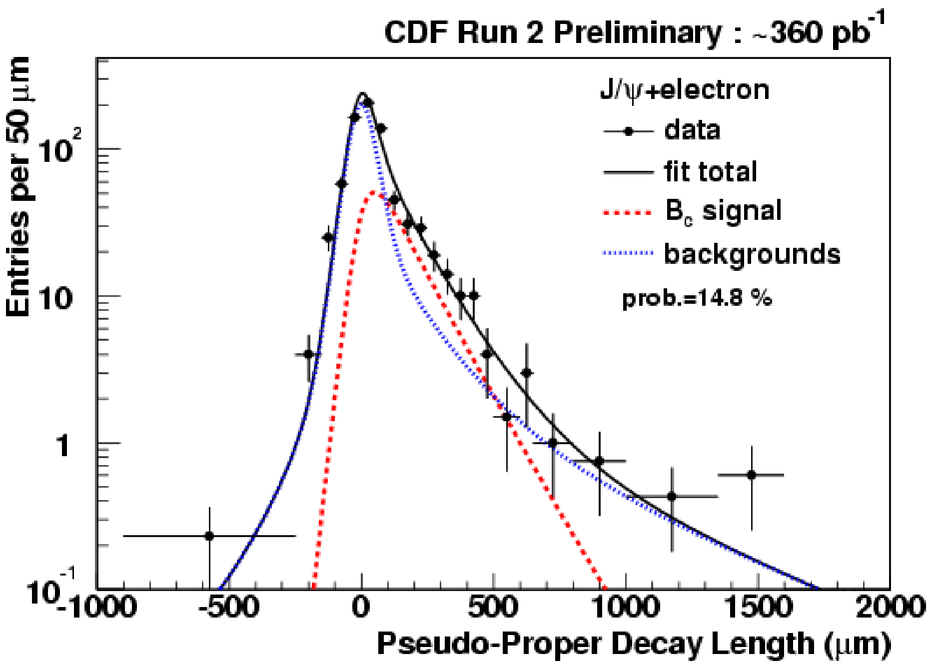
Background: 63.6 ± 4.9 ± 13.6
Signal: 114.9 ± 15.5 ± 13.6

- J/ψ collected on dimuon triggers
- Electrons selected using a 10 variable likelihood function
  - PDF for electrons from conversions
  - PDF for pion, kaon, proton similar so use $K_s \rightarrow \pi\pi$

Background estimated using hadron tracks, electrons tagged as conversions and MC

Probability of background to fluctuate to signal is 3.2×10^{-9} which is a significance of 5.9 σ

Results



$$\frac{\sigma(B_c)\times BR(B_c \to J/\psi e \nu)}{\sigma(B^+)\times BR(B^+ \to J/\psi K^+)} = \frac{N(B_c)}{N(B^+)} \times R^K \times R^\varepsilon$$

R^K is kinematic acceptance ratio
R^ε is trigger and reconstruction Efficiency ratio

$P_T(B) > 4$ GeV and $|y(B)|<1$

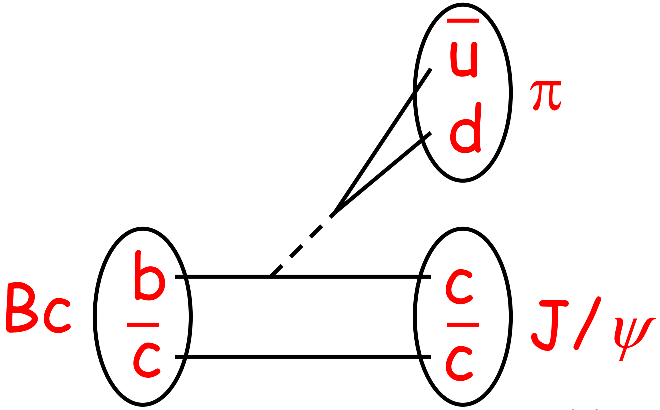
0.282 ± 0.038(stat) ±0.035 (yield) ± 0.065 acceptance

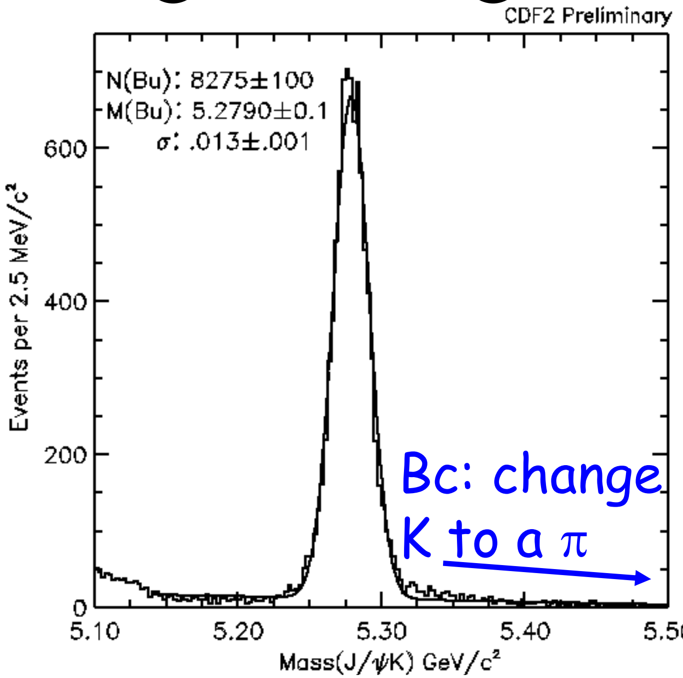
$\tau(B_c)$ = 0.474 + 0.073 – 0.066 ± 0.033 (sys) ps

$\tau(B_c)$= 0.448 +0.123 – 0.096 ± 0.121 ps DØ

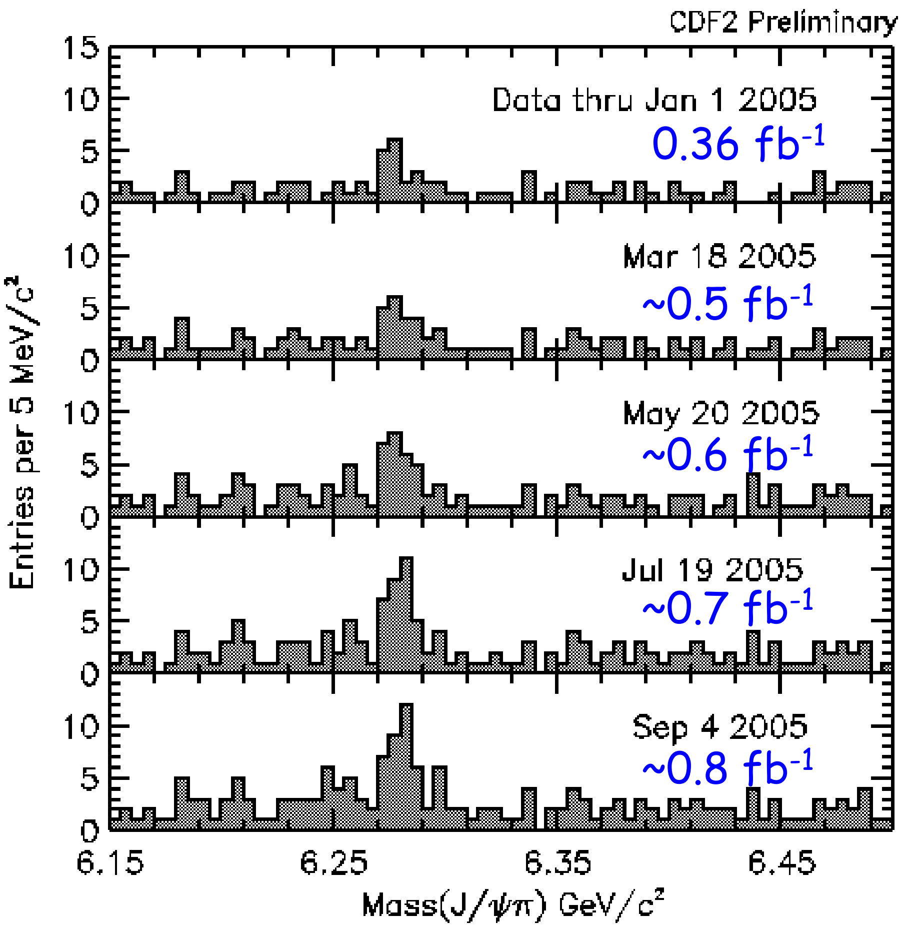
B_c -> J/ψ π

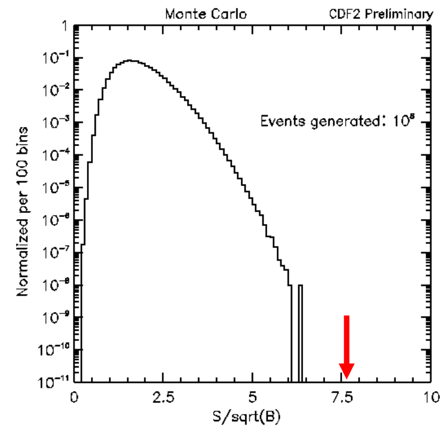
- Full reconstruction allows for precise mass measurement
- New analysis
  - Tune selection on the data: B_u -> J/ψ K reference decay
  - After approval, “open box”.
  - Wait for events to become a significant excess
  - Measure properties of the B_c





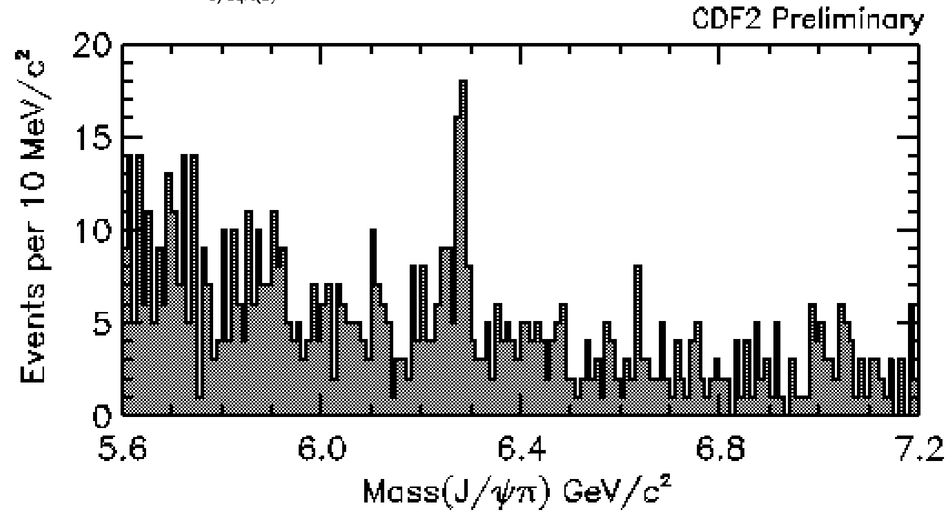
$B_c \rightarrow J/\psi\ \pi$





Num(events)$_{FIT}$=
38.9 sig 26.1 bkg
between 6.24-6.3

Significance > 6σ
over search area

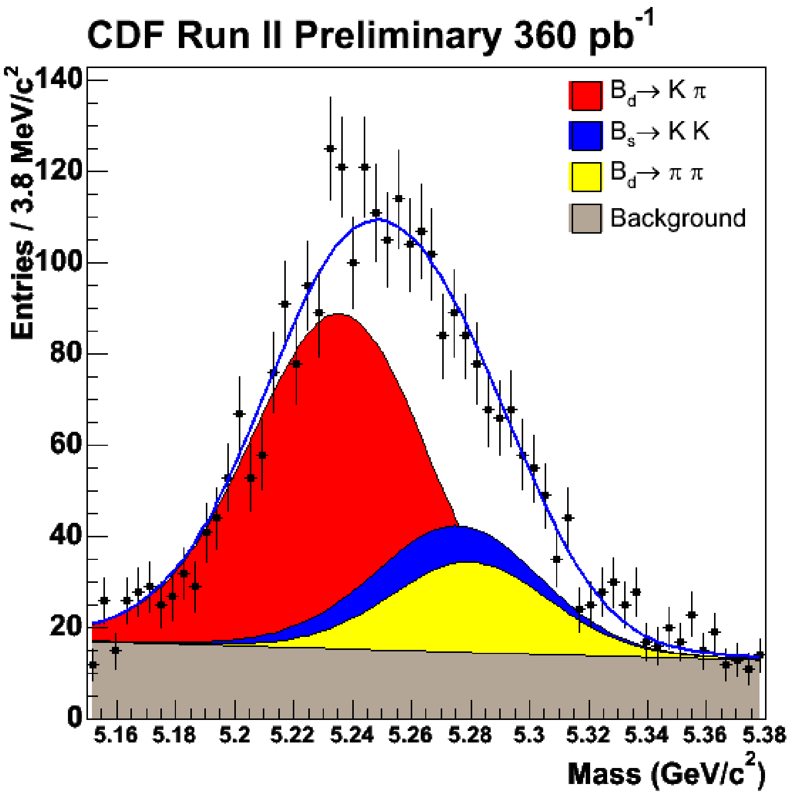


Mass(B_c) = 6275.2 +/- 4.3 +/- 2.3 MeV/c^2

Best in world!

$B_s \rightarrow K^+K^-$ lifetime

- Displaced vertex trigger allows for triggering of events
- $B \rightarrow hh$ mass peak dominated by 4 major decay modes $B_d \rightarrow K^+\pi^-$, $B_d \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$, $B_s \rightarrow K^-\pi^+$
- $B_s \rightarrow KK$ CP even state so $\Delta\Gamma$ can be extracted by comparing to other measurements
- Relative signal fractions and B_d and B_s lifetimes extracted using a combined multidimensional unbinned likelihood fit
  - $M\pi\pi$
  - $q1(1-p_1/p_2)$ where $p_1<p_2$
  - p_1+p_2
  - dE/dX
  - $c\tau$
  - $\sigma_{c\tau}$



Fit Results

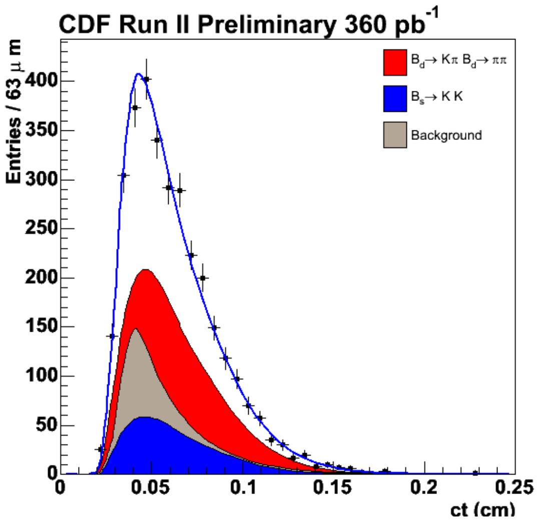
- B_d fit consistent with PDG value (460.8 ± 4.5 μm)
- Fix B_d lifetime to PDG value

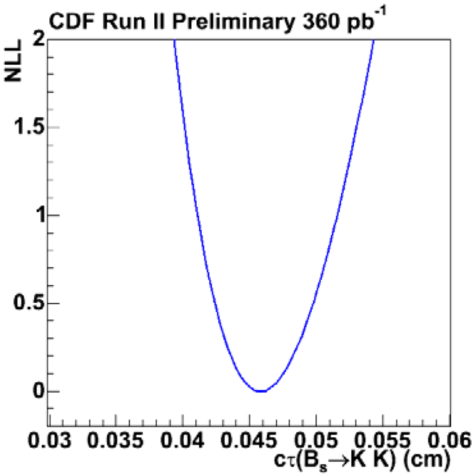
- $f(B_d \to K\pi)$=62.7 ±1.7%
- $f(B_d \to \pi\pi)$=15.3 ± 1.5%
- $f(B_s \to KK)$ = 22.3 ± 1.7%
- $f(B_s \to K\pi)$= -0.3 ± 1.0%
- f(BKG)=27.8 ± 0.4 %

$c\tau(B_s \to K^+K^-)$ = 1.53 ± 0.18(stat) ± 0.02(sys) ps

Using HFAG B_s lifetime in flavor specific decays

$$\frac{\Delta\Gamma_{CP}}{\Gamma_{CP}}\left(B_s \to K^+K^-\right) = -0.08 \pm 0.23 \pm 0.03$$





Dimuon charge asymmetry

- CP violation in $K^0 \leftrightarrow \overline{K^0}$ described by ε_K
- ε_{B0} is the CP violating parameter in $(B^0,\overline{B^0})$ system
- Dimuon charge asymmetry A
- Assuming A is due to asymmetric $B^0 \leftrightarrow B^0$ mixing

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

$$\frac{\Re(\varepsilon_{B^0})}{1 + |\varepsilon_{B^0}|^2} = \Im\left\{\frac{\Gamma_{12}}{4M_{12}}\right\} = \frac{A_{B^0}}{4} \equiv f\,A$$

$M_{12}(\Gamma_{12})$ is real(imaginary) part of transition Matrix element of Hamiltonian corresponding to B_0,B_0 mixing and decay. A_{B^0} is dimuon charge asymmetry from direct-direct decays of B_0B_0 pairs

SM: $A_B{}^0$= -0.0005 ± 0.00011
World Average: 0.002 ± 0.013

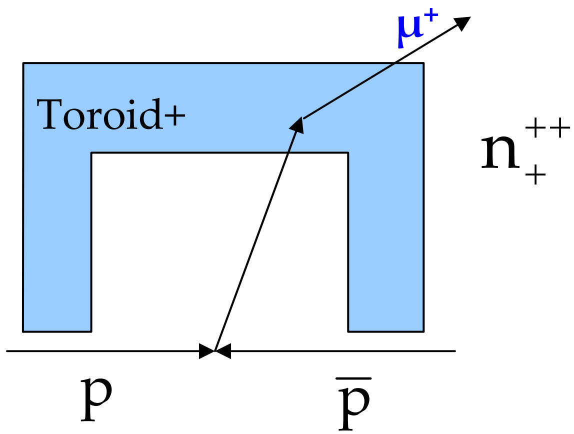
The asymmetry is sensitive to several extensions to the SM

Extracting Physics Asymmetry

- In the ideal symmetric world and symmetric detector:

$$n_q^{\beta\gamma} = \frac{1}{4} N \, \varepsilon^{\beta}$$

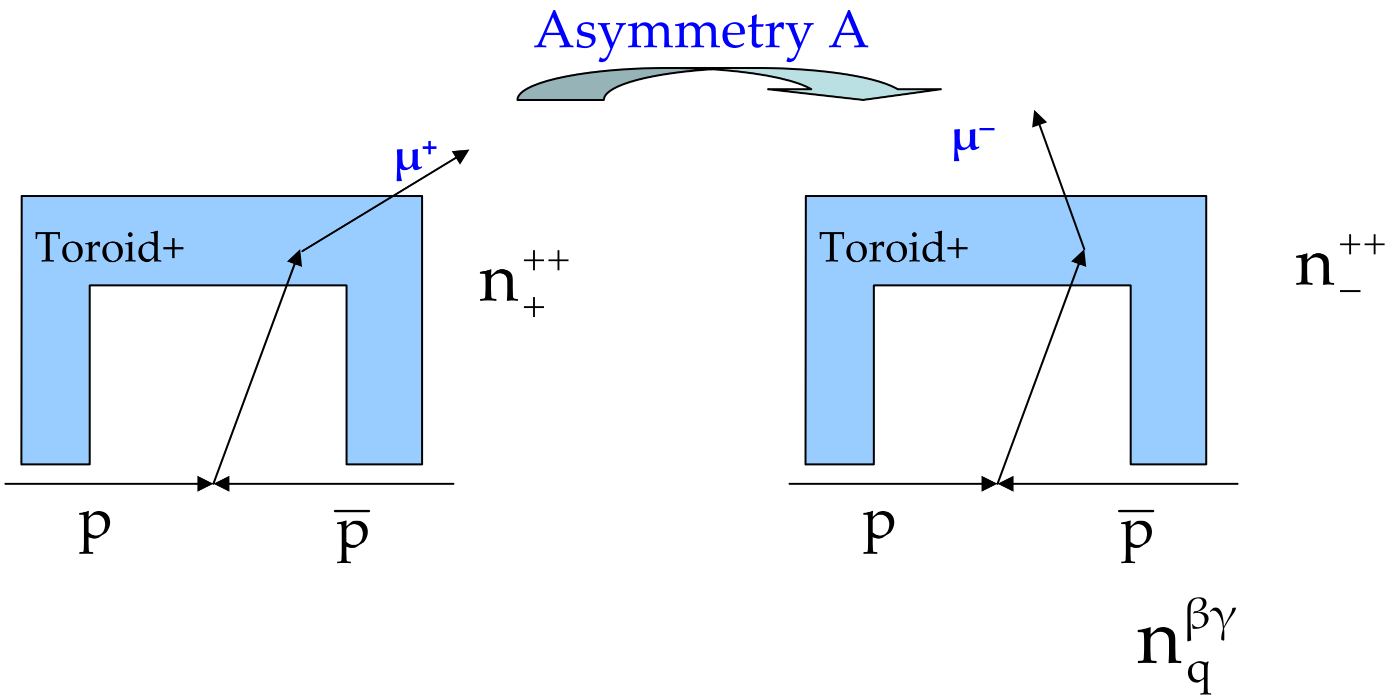
- **q - charge of a muon (q = ±1);**
- **β - Polarity of toroid (β = ±1);**
- **γ - muon direction, γ = +1 for η > 0; γ = –1 for η < 0;**
- **ε^{β} - fraction of integrated luminosity with toroid polarity β;**
- **N - number of selected muons (in dimuon events!)**



Extracting Physics Asymmetry

- **Physics asymmetry A between positive and negative muons related to CP violation :**

$$n_q^{\beta\gamma} = \frac{1}{4} N \, \varepsilon^{\beta} (1 + q\,A)$$



Asymmetries

$$n_q^{\beta\gamma} = \frac{1}{4} N \varepsilon^{\beta} (1+q A)(1+q\gamma A_{fb})(1+q\beta A_{q\beta})(1+\gamma A_{det})(1+q\beta\gamma A_{ro})(1+\beta\gamma A_{\beta\gamma})$$

2 Physics asymmetries A, A_{fb}
4 Detector asymmetries
ε^{β}, N

→ 8 unknowns, 8 $n_q^{\beta\gamma}$

- Muon toroid polarity is regularly reversed which allows a measure of detector related asymmetries.

$$\frac{(n_+^{++} + n_+^{+-} - n_-^{++} - n_-^{+-}) + e(n_+^{-+} + n_+^{--} - n_-^{-+} - n_-^{--})}{(n_+^{++} + n_+^{+-} + n_-^{++} + n_-^{+-}) + e(n_+^{-+} + n_+^{--} + n_-^{-+} + n_-^{--})} = A + A_{fb} A_{\det}$$

A dimuon charge asymmetry, A_{fb} is forward-backward asymmetry (tendency for μ+ to go in proton direction and μ- to go in anti-proton direction. A_{det} detector asymmetry. $e=\varepsilon+/\varepsilon-$.

Detector asymmetries small (before averaging over polarities) < 0.006 on dimuon charge asymmetry

Dimuon processes

- Probability that a b quark mixes and decays as a $\bar{b}$ is

$$\chi = f_d \frac{\beta_d}{\langle \beta \rangle} \chi_d + f_s \frac{\beta_s}{\langle \beta \rangle} \chi_s$$

f_d, fs – fractions of b-hadrons that are produced as B^0 or B_s

β_d,β_s and <β> are branching fractions for B^0,B_s and b-hadron admixture decaying to μX

Study this distribution to see if $\chi_d = \bar{\chi}_d$

Compare χ to known value to ensure no biases in measurement

Need to take into account many dimuon processes:

$b \to \mu^-$, $b \to \mu^+$
$b \to \mu^-$,$b \to c \to \mu^-$
$b \to c \to \mu^+$, $b \to c \to \mu^-$
$b \to \mu^- c \to \mu^+$
$c \to \mu^+$,$c \to \mu^-$
Drell Yan, J/ψ, Y

Dimuon cosmic rays
μ + $K^{\pm}$ decays
μ + cosmic
μ +punchthrough
μ +combinatoric

Results

1 fb^{-1}

$$\frac{\Re(\varepsilon_{B^0})}{1+|\varepsilon_{B^0}|^2} =$$

-0.0011 ± 0.0010(stat) ± 0.0007 (sys) (D0 preliminary)
PDG: 0.0005 ± 0.0031

- Mixing probability averaged over the mix of hadrons with a b quark
  $\langle\chi\rangle$= 0.136 ± 0.001(stat) ± 0.024(sys) (D0 preliminary)
  PDG: $\langle\chi\rangle$ = 0.127 ± 0.006

- A_{fb}= 0.0004 ± 0.0004(stat) ± 0.0001(sys) (D0 preliminary)

Conclusion

- Tevatron is providing a rich program in B physics
  - Physics results using 1 fb^{-1} of data
  - Measuring properties of B**
  - First Observation of B^*_{S2}
  - Improving Λ_b and B_c lifetime measurement
  - World's best measurement of B_c mass
  - New Channel for Measuring $\Delta\Gamma/\Gamma$
  - World's best measurement of ε_{B0}

- Tevatron currently in shutdown
  - DØ will be adding in a L0 silicon detector. Provide much better vertex resolution. Hope to soon increase bandwidth for B physics
  - CDF improve silicon vertex trigger to allow increase of factor of 2 trigger rate. Improve tracking trigger and PC farm to increase purity and utilize higher b physics rate

- Data sample will continue to increase and detectors are being improved so B physics at the Tevatron will continue for many years.