Heavy Flavor Spectroscopy at the Tevatron

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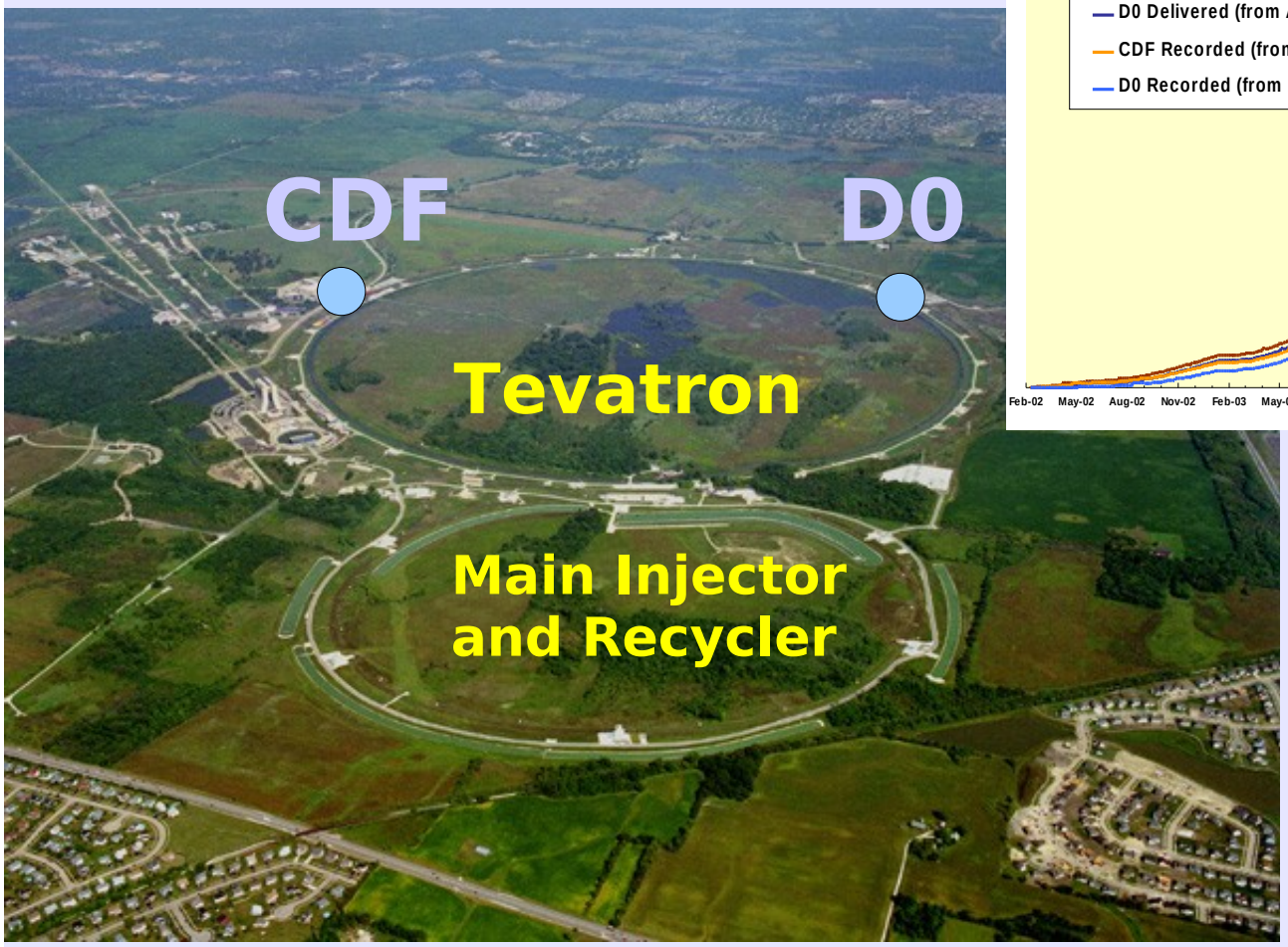
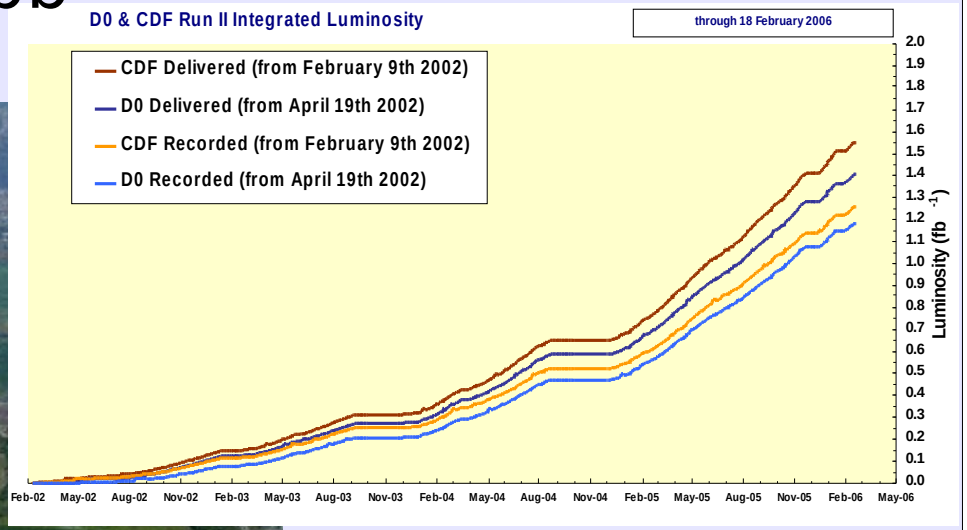
Topics

- b hadron production
- X(3872) studies
- B_c observation and properties
- orbitally excited B, D mesons
- Λ_b lifetimes

Tevatron

- machine delievered >1.5 fb^{-1}
- CDF and D0 recorded >1.2 fb^{-1}
- analyses use 200 to 1000 pb^{-1}





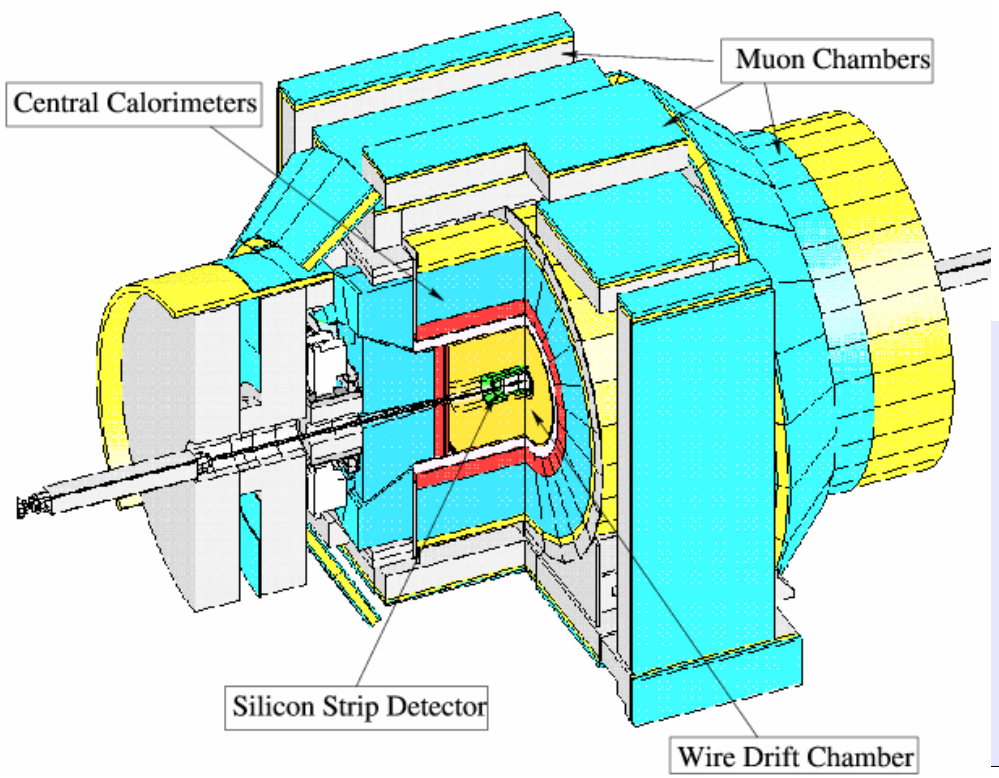
$p\bar{p}$ collisions

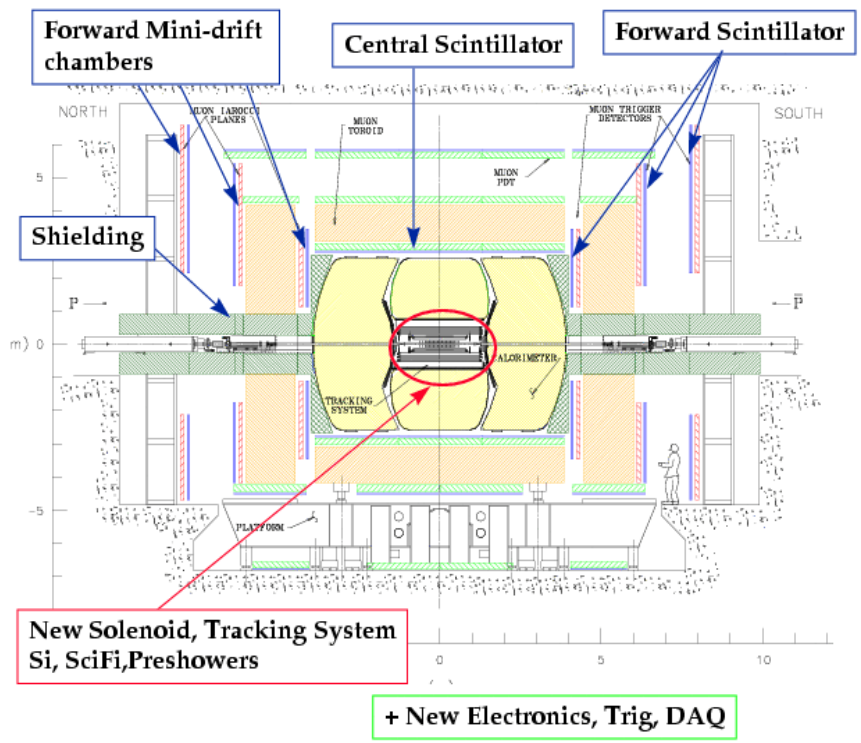
CM 1.96

CDF and D0 Experiments

CDF:

- great ***m*** and ***p*** resolution
- displaced track triggers
- triggered μ to |η|<1.1



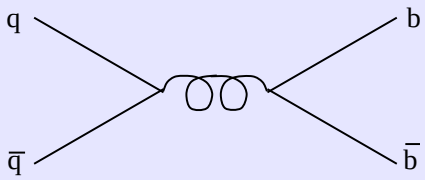


D0 Upgrade

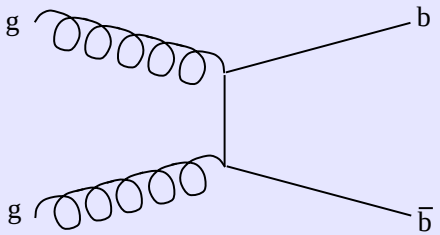
D0:

- triggered μ to |η|<2.0
- good electron ID
- trigger tracking to|η|<2.0

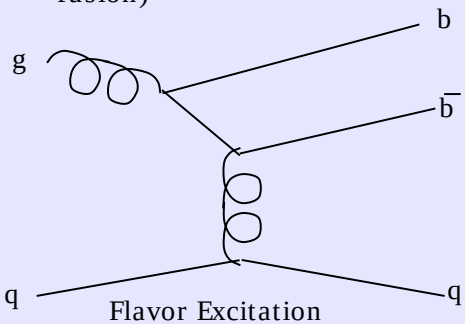
Heavy Flavor Physics at Tevatron



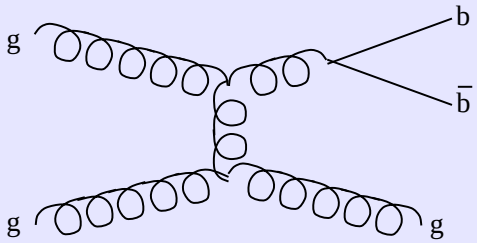
Flavor Creation (annihilation)



Flavor Creation (gluon fusion)



Flavor Excitation



Gluon Splitting

Tevatron is great for heavy flavor:

- b production x-section x1000 than at e^+e^- B factories
- all b and c hadrons produced
  - B^0, B^+, B_s, Λ_b, B_c, Ξ_b, etc
  - D^0, D^+, D_s, Λ_c, χ_c, Ξ_c, X(3872), etc

However:

- inelastic (QCD) background is x1000 higher than b x-section
- online triggering and reconstruction is a challenge
- collision rate ~1 Mhz, writing to tape at ~100 Hz

b Hadron Production Fractions

Rate of b quark fragmentation to form mesons and baryons:

- compare samples of B^0, B^+, B_s and $\Lambda_b \Rightarrow$ get f_u, f_d, f_s and $f_{\Lambda b}$
- B* and B** are not disentangled
- measure relative fractions f_u/f_d , $f_s/(f_u+f_d)$ and $f_{\Lambda b}/(f_u+f_d)$

Using semileptonic B and Λ_b decays, CDF measures on 360 pb-1:

$$\begin{aligned}
\frac{f_s}{f_u+f_d} \times \mathcal{BR}(D_s^+ \to \phi\pi^+) &= (5.76 \pm 0.18(stat)^{+0.45}_{-0.42}(sys)) \times 10^{-3} \\
\frac{f_{\Lambda_b}}{f_u+f_d} \times \mathcal{BR}(\Lambda_c^+ \to pK^-\pi^+) &= (14.1 \pm 0.6(stat)^{+5.3}_{-4.4}(sys)) \times 10^{-3} \\
\frac{f_{\Lambda_b}}{f_u+f_d} \times \mathcal{BR}(\Lambda_b^0 \to \ell\nu\Lambda_c^+)\mathcal{BR}(\Lambda_c^+ \to pK^-\pi^+) &= (12.9 \pm 0.6(stat) \pm 3.4(sys)) \times 10^{-4}
\end{aligned}$$

$$\begin{aligned}
\frac{f_u}{f_d} &= 1.054 \pm 0.018(stat)^{+0.025}_{-0.045}(sys) \pm 0.082(\mathcal{BR}) \\
\frac{f_s}{f_u+f_d} &= 0.160 \pm 0.005(stat)^{+0.011}_{-0.010}(sys)^{+0.057}_{-0.034}(\mathcal{BR}) \\
\frac{f_{\Lambda_b}}{f_u+f_d} &= 0.281 \pm 0.012(stat)^{+0.058}_{-0.056}(sys)^{+0.128}_{-0.086}(\mathcal{BR}).
\end{aligned}$$

$f_{\Lambda b}$ higher then LEP by ~2.2 σ

The mystery of X(3872)

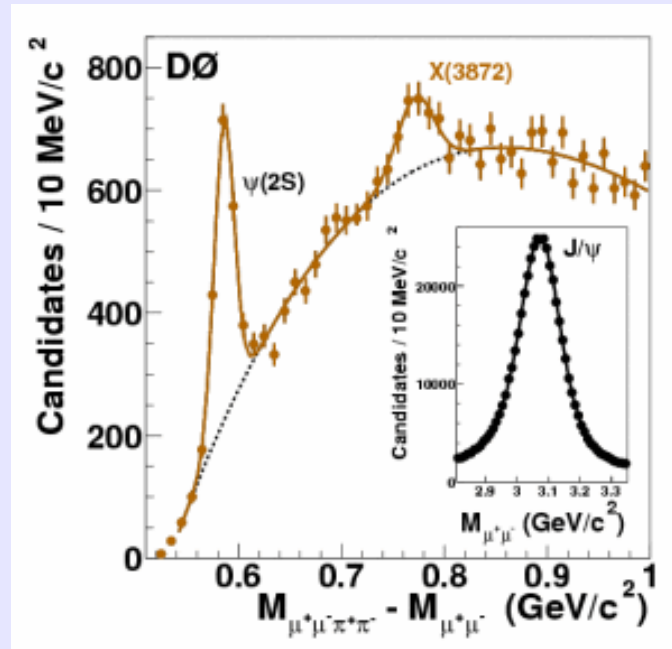
Aug'03: Belle annonunces discovery of $X(3872) \to J/\psi \pi^+ \pi^-$

What is it? Pros/cons for any explanation

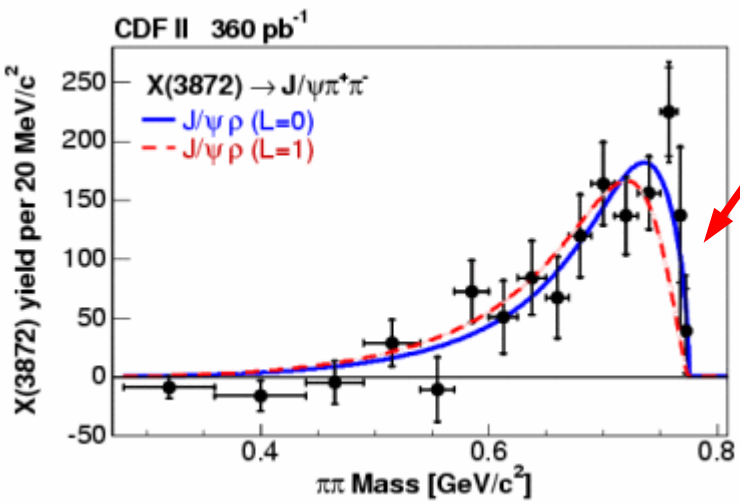
- DD* molecule?
- Excited ccbar state

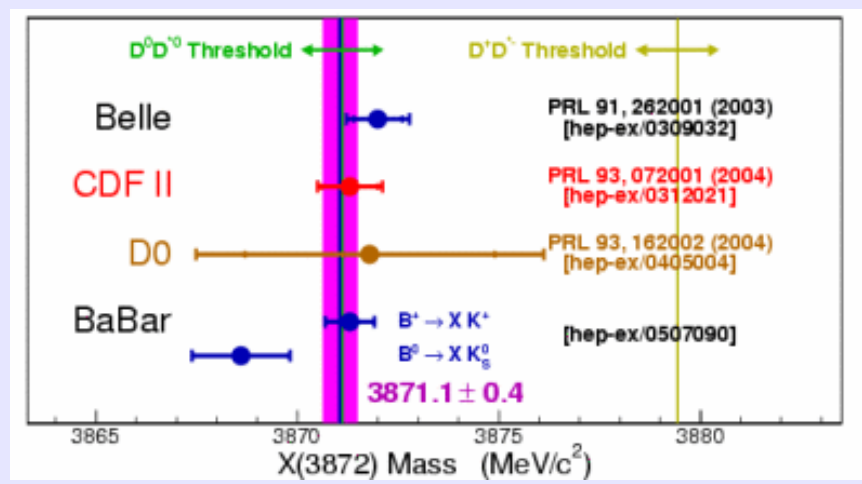
Results from CDF and D0 rapidly follow

- observation and mass at ppbar
- production properties, prompt fraction
  ➔ consistent with $\Psi(2S)$
- $(\pi\pi)$ mass spectrum:
  ➔ first glimpse of quantum numbers
- see: hep-ex/0505083, hep-ph/0506222, hep-ph/0508258



looks like $J/\Psi\ \rho$

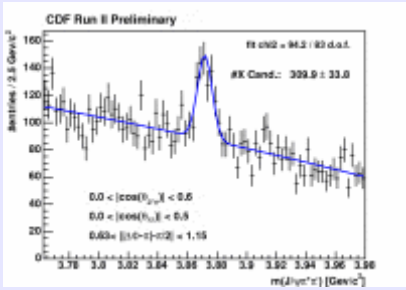




X(3872): angular analysis

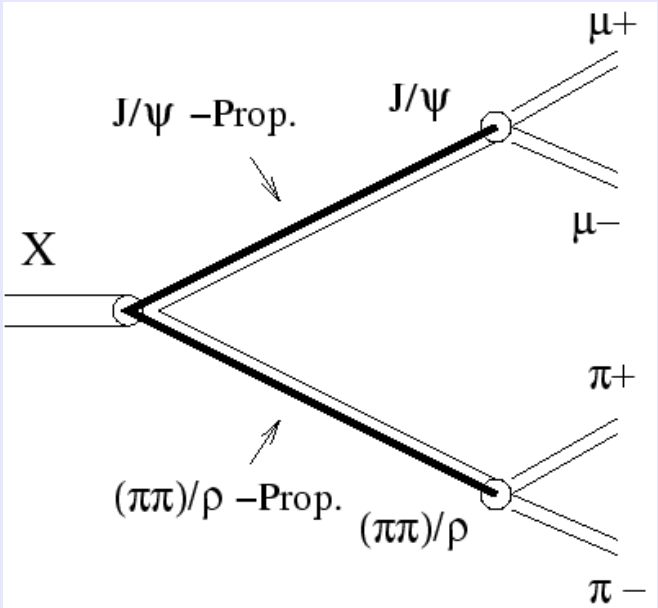
CDF seeks to determine J, P and C of the X(3872)

Example:



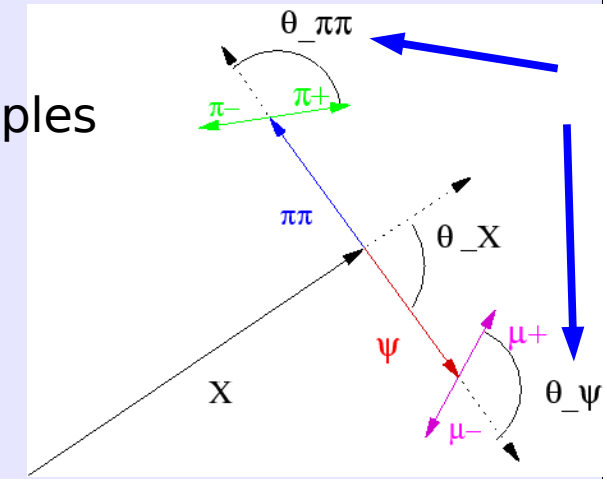
a sample of ~3000 of X(3872) candidates with 780 pb^{-1} of data

derive predictions for decay angle distributions for different J^{PC}

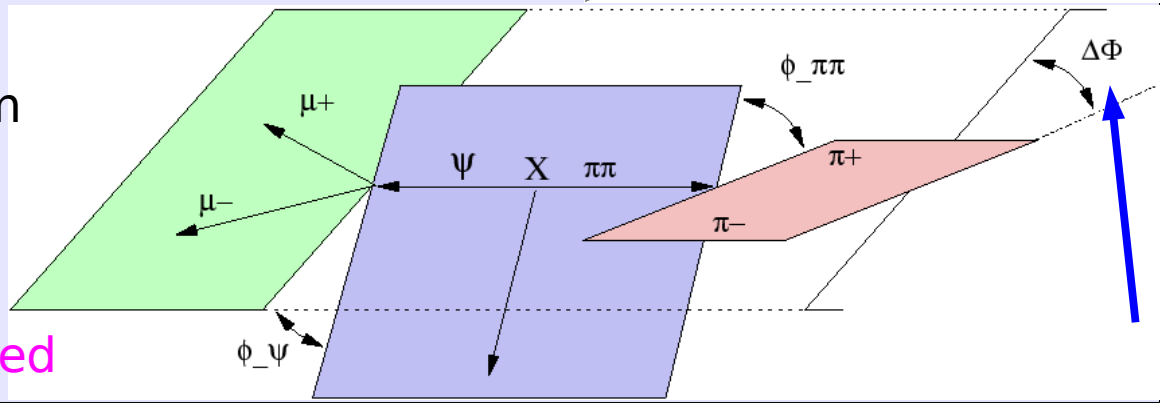


Fit m(X) in 3x2x2 subsamples

- 3 bins in $\Delta\Phi$
- 2 bins in cos Θ_{ψ}
- 2 bins in cos $\Theta_{\pi\pi}$



L=0 or 1 assumed for (ππ) system



Cross-check on Ψ(2S):

- same final state, J^{PC} reproduced

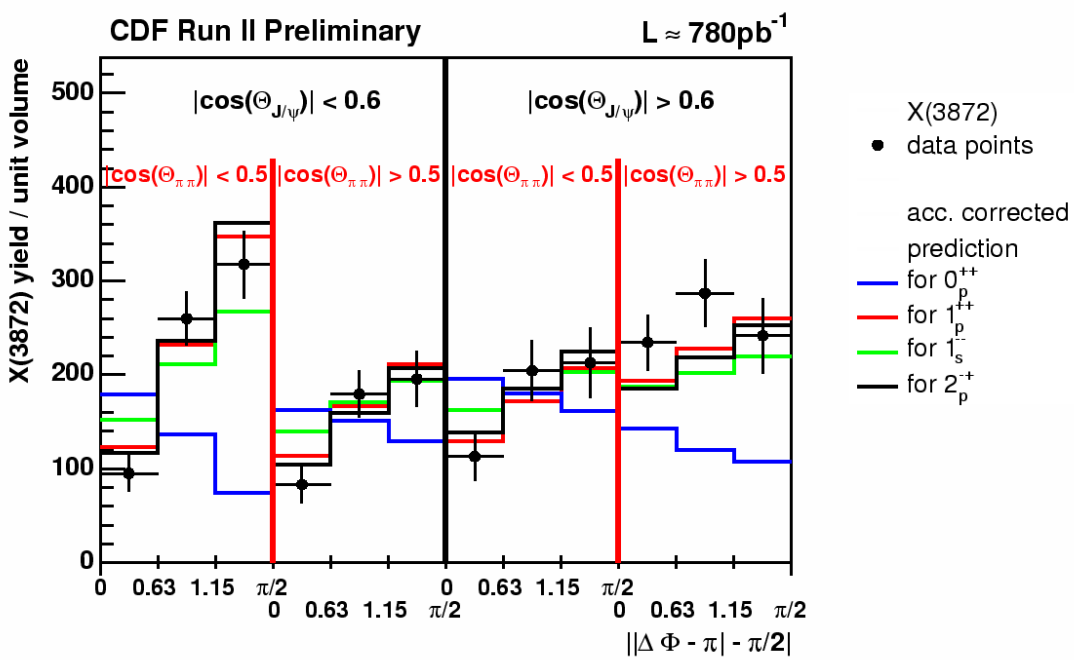
X(3872): results for J^{PC}

Simultaneous fit of 3 angles: $\Delta\Phi$, Θ_ψ and $\Theta_{\pi\pi}$

- 12 data points from mass fits

Derive probability: many J^{PC} hypotheses

hypothesis	3D χ^2 / 11 d.o.f.	χ^2 prob.
1^{++}	13.2	27.8%
2^{-+}	13.6	25.8%
1^{--}	35.1	0.02%
2^{+-}	38.9	$5.5\cdot10^{-5}$
1^{+-}	39.8	$3.8\cdot10^{-5}$
2^{--}	39.8	$3.8\cdot10^{-5}$
3^{+-}	39.8	$3.8\cdot10^{-5}$
3^{--}	41.0	$2.4\cdot10^{-5}$
2^{++}	43.0	$1.1\cdot10^{-5}$
1^{-+}	45.4	$4.1\cdot10^{-8}$
0^{-+}	103.6	$3.5\cdot10^{-17}$
0^{+-}	129.2	$\leq 1\cdot10^{-20}$
0^{++}	183.1	$\leq 1\cdot10^{-20}$



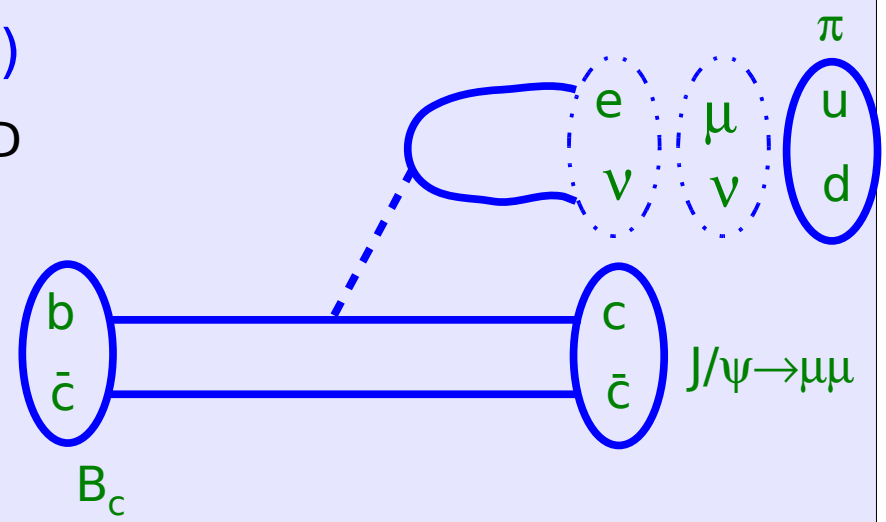
Result:

- only J^{PC}=**1^{++}** and **2^{-+}** fit to data
- all others excluded by >3σ

B_c: introduction

Bound state of two heavy quarks (bc)

- good lab for potential models, lattice QCD
- b,c – different flavors
- only weak decays possible



Experimental knowledge:

- first observed by CDF in '98 in semileptonics
  - properties not well measured
- higher statistics in Run II
  - more precise lifetime
  - access to exclusive modes ⇒mass measurement

Challenging: low production rate

- $B^0:B^+:B_s:\Lambda_b \approx 40:40:10:10$, $B_c \sim 0.5\%$
- short lifetime ⇒difficult selection

B_c: observation and mass

We reconstruct B_c in 3 channels:

$B_c \to J/\psi\, e\, \nu$ CDF

$B_c \to J/\psi\, \mu\, \nu$ CDF, D0

} semileptonics: good for lifetime (sufficient yields)

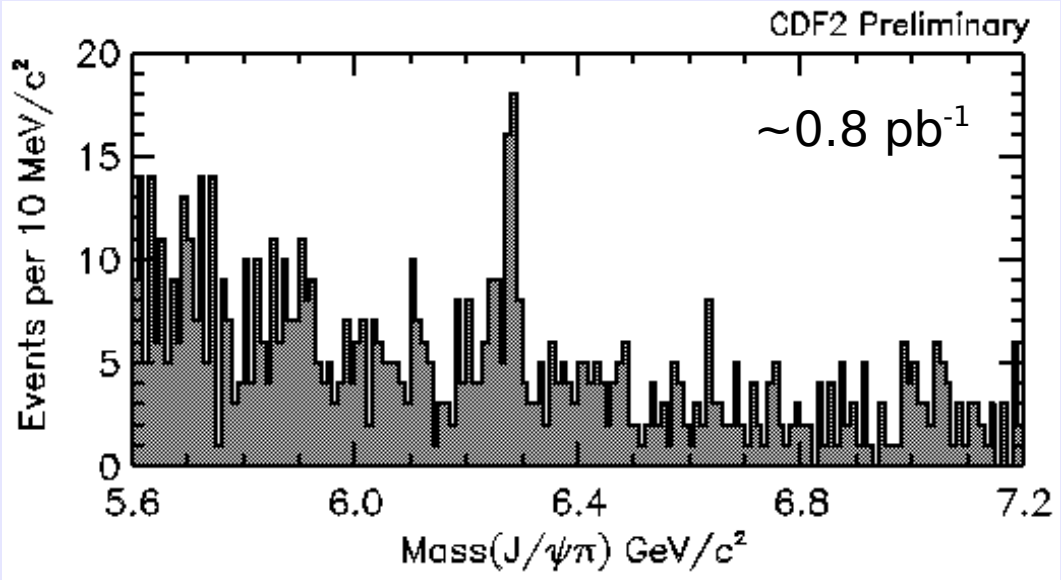
$B_c \to J/\psi\, \pi$ CDF

} hadronic decays: good for mass (fully reconstructed)

At present, 6σ or more signal is observed in all these channels!

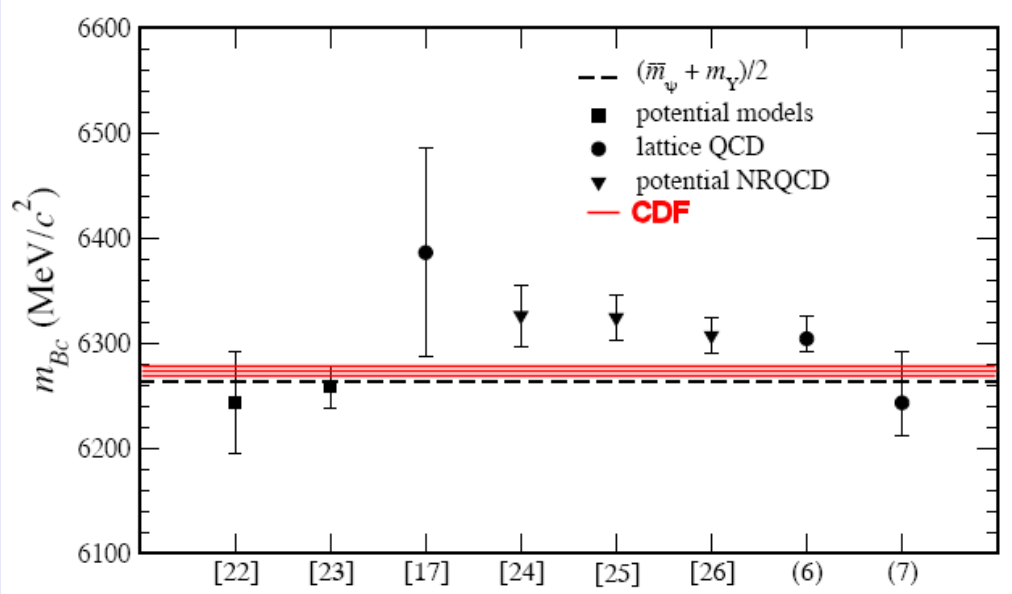
CDF: fully reconstructed $B_c \to J/\Psi\pi$ sample for mass measurements

$M(B_c)=6275.2\pm4.3\pm2.3$ MeV/c²



B_c: lattice results vs CDF

Lattice calculations that show good agreement with experiment were used to *predict* the mass of the B_c



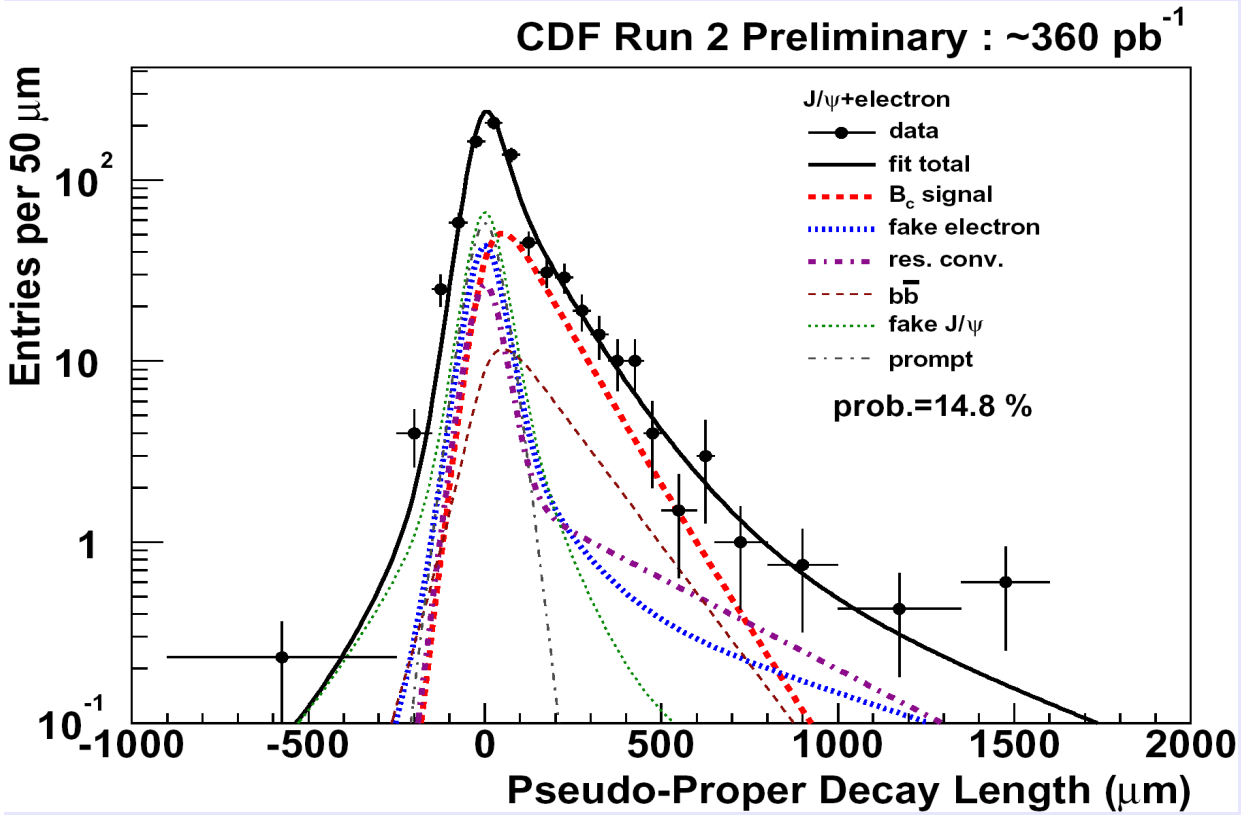
PRL 94, 1720001 (2005)

$$M(B_c)_{CDF} = 6275.2 \pm 4.3 \pm 2.3 \text{ MeV}/c^2$$

$$M(B_c)_{LAT} = 6304 \pm 12^{+18}_{-0} \text{ MeV}/c^2$$

B_c: lifetime measurement

- Bc lifetime extracted from $B_c \rightarrow J/\psi\, l\, \nu$ samples



- more stat than hadronic mode
- but also more background too

World's best

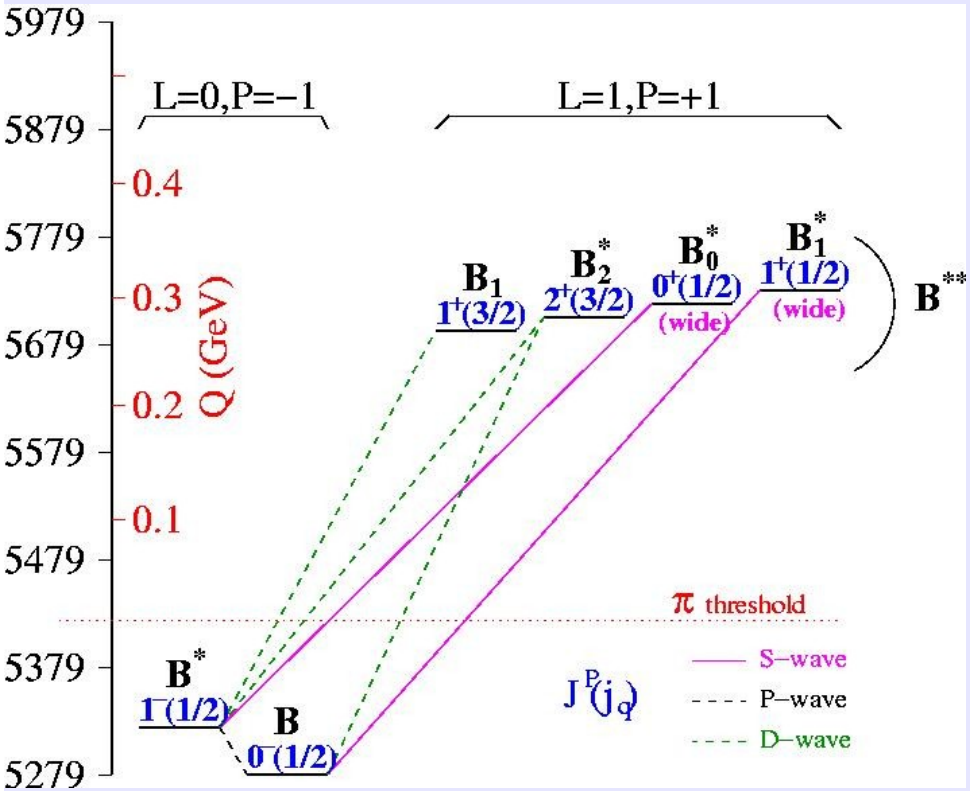
CDF: lifetime measured in J/Ψe channel: $0.474^{+0.073}_{-0.066} \pm 0.033$ ps on 360 pb^{-1}

D0: J/Ψμ channel: $0.448^{+0.123}_{-0.096} \pm 0.121$ ps on 210 pb^{-1}

Theoretical prediction: 0.55+-0.15 ps (V. Kiselev, hep-ph/0308214)

B**: introduction

B* and B** or B_J: first orbital excitations of (bq) system



Qualitative picture well understood:

- 4 of P-states: B^*_0, B^*_1, B_1, B^*_2
- B^*_0, B^*_1 are wide (~100 MeV) states, decay via S-wave
- B_1, B^*_2 are narrow (~10 MeV) states, decay via D-wave
- B^*_2 can decay to $B^*\pi$ and $B\pi$
- B_1 can decay only to $B^*\pi$

Quantitative understanding is worse:

- predictions for m, Γ and decay properties depend on many model parameters

From Tevatron: focus on narrow states for now

B** narrow states from D0

Decay channels: find $B^{**} \rightarrow B^{(*)}$ - as

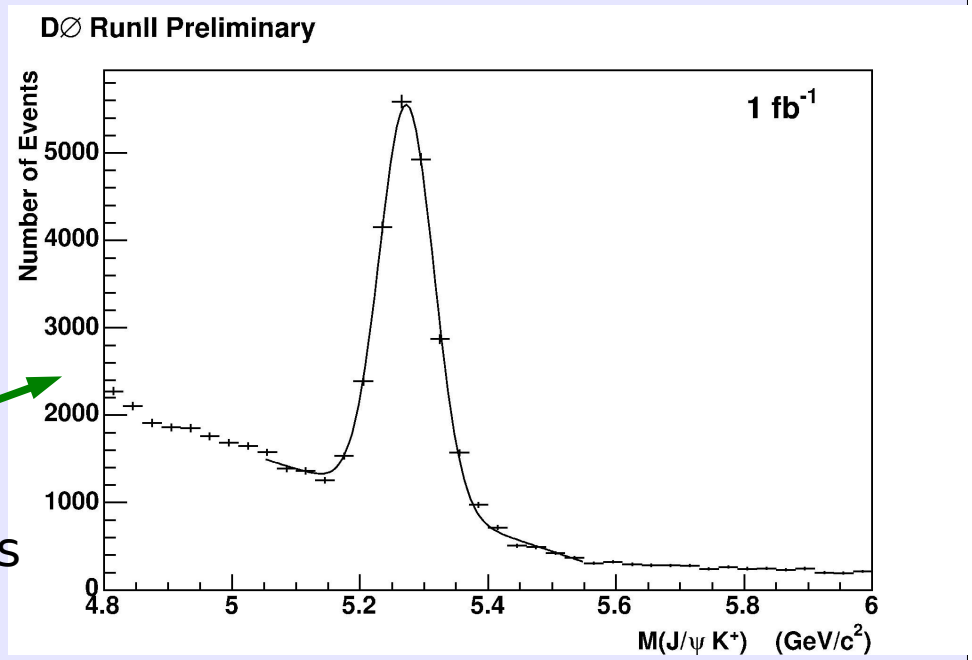
$$B_1^0 \rightarrow B^{*+}\pi^-; \quad B^{*+} \rightarrow B^+\gamma$$

$$B_2^{*0} \rightarrow B^{*+}\pi^-; \quad B^{*+} \rightarrow B^+\gamma$$

$$B_2^{*0} \rightarrow B^+\pi^-$$

Reconstruction:

- based on 16K of $B^+ \rightarrow J/$ K^+ candidates
- photon in $B^* \rightarrow \gamma B$ not reconstructed



Add events from all 3 modes, fit mass difference M(B) – M(B)

Constrained:

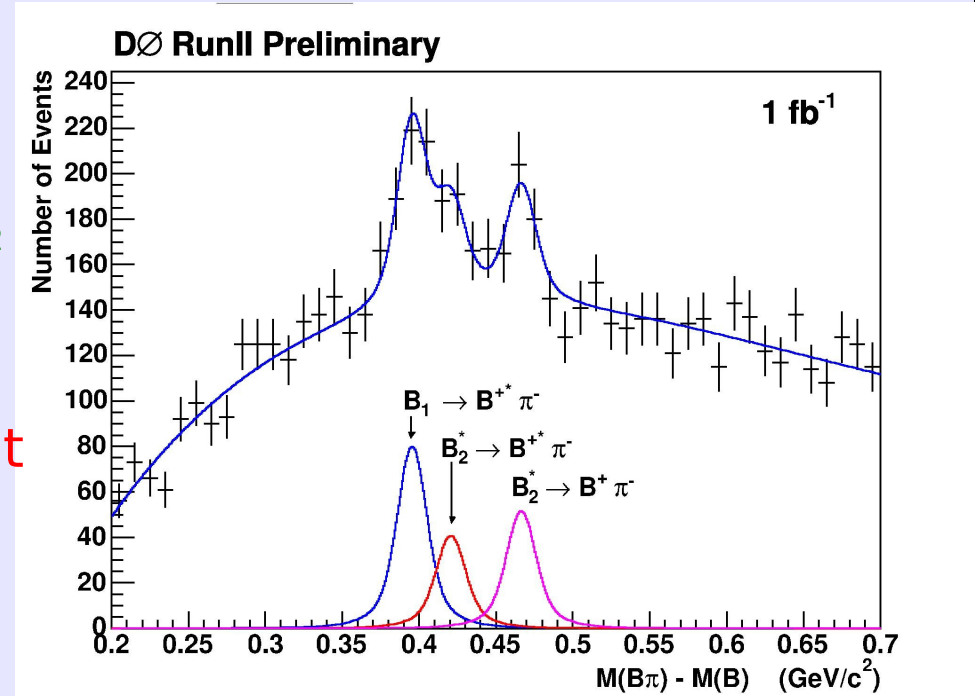
- (B$_1$) = (B$_2^*$) = Γ from theoretical expectations (Γ floats)
- also, M(B*)-M(B$^+$)=45.78 MeV/c^2 [PDG]

B**: results from D0

First observation of separate peaks at hadron collider

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

$M(B^*_2) - M(B_1) = 25.2 \pm 3.0 \pm 1.1$ MeV/c^2



The only narrow width measurement

$\Gamma(B_1) = (B_2^*) = 6.6 \pm 5.3 \pm 4.2$ MeV/c^2

Production rates:

$$\frac{BR(b \to B_J^0 \to B\pi)}{BR(b \to B^+)} = 0.165 \pm 0.024 \pm 0.028$$

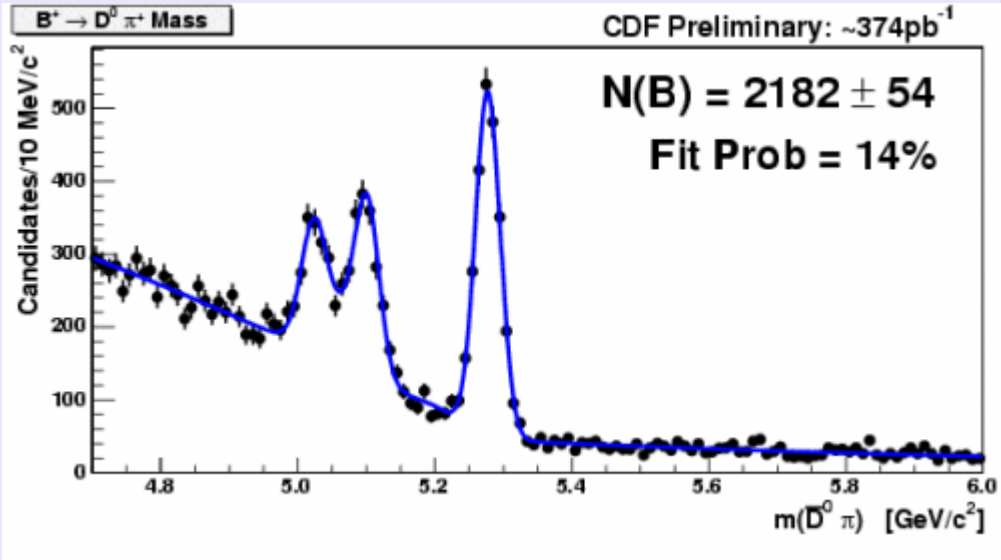
$$\frac{BR(B_2^* \to B^*\pi)}{BR(B_2^* \to B^{(*)}\pi)} = 0.513 \pm 0.092 \pm 0.115$$

$$\frac{BR(B_1 \to B^{*+}\pi)}{BR(B_J \to B^{(*)}\pi)} = 0.545 \pm 0.064 \pm 0.071$$

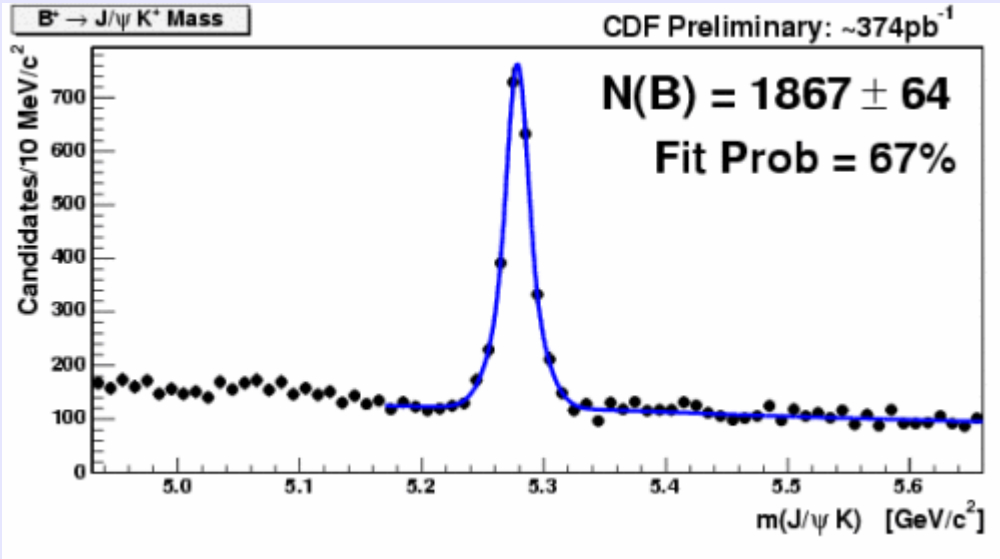
B** narrow states from CDF

Reconstruct $B^{**0} \rightarrow B^{(*)+}$ $^{-}$:

- B^{+} decay: $B^{+} \rightarrow J/$ K^{+}
- and $B^{+} \rightarrow D^{0}$ $^{+}$



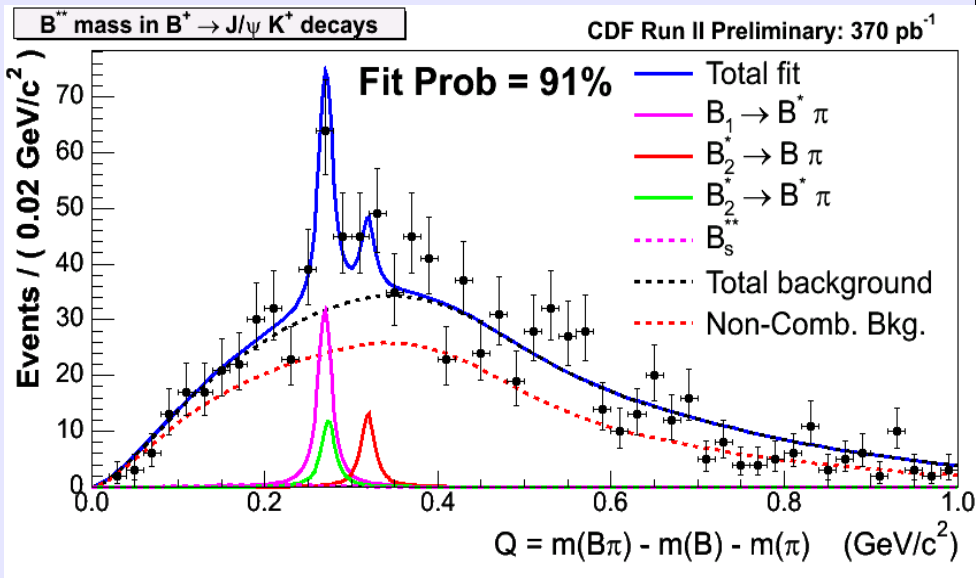
Events in sidebands of B+ mass are later used to determine the combinatorial background in B** mass fits



D* background to D^{0} $^{+}$ is suppressed in selection

B**: results from CDF

Fit $M(B\ \ )-M(B)-M(\ \ )$ simultaneously for all channels

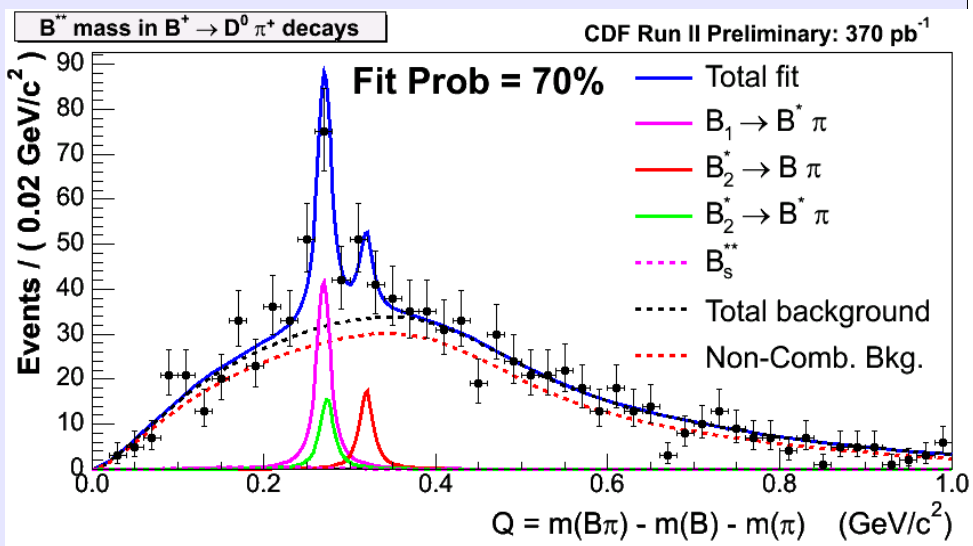


Low statistics ⇒fix width to theoretical value $(B_2^{*0}) = 16 \pm 6\,\mathrm{MeV}/c^2$ (hep-ph/9507311)

- also, fix $(B_1^0) = (B_2^{*0})$

Fix $\dfrac{Br(B_2^{*0} \to B^*\ \ )}{Br(B_2^{*0} \to B\ \ )} = 1.1 \pm 0.3$

Delphi 2004-025 conf 700



World's best mass measurements:

$M(B_1^0) = 5734 \pm 3 \pm 2\,\mathrm{MeV}/c^2$

$M(B_2^{*0}) = 5738 \pm 5 \pm 1\,\mathrm{MeV}/c^2$

Search for B^*_{s2} at D0

B^{**}_s: similar hierarchy of orbital excitations as for B^{**}

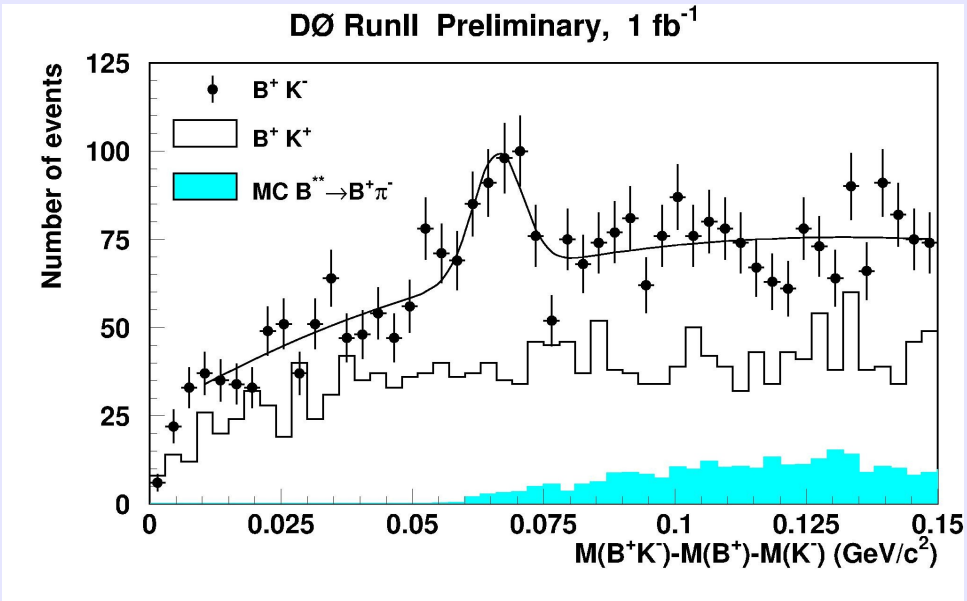
- wide states B^*_{s0} and B^*_{s1}
- narrow states B_{s1} and B^*_{s2}
- even less well studied than B^{**}

The signature:

- due to isospin conservation decays to $B_s\pi$ highly suppressed
- search for excited states decaying to B^+K^-
- use the same $B^+ \rightarrow J/\quad K^+$ sample as for the B^{**} search
- 1 fb^{-1} of data

B^*_{s2}: first direct observation

Fit mass difference: $M(B^+K^-)-M(B^+)-M(K^-)$



First direct observation of B^*_{s2}, significance of the peak >5σ!

$M(B^*_{s2})=5839.1\pm1.4\pm1.5$ MeV/c^2

Checks:

- no evidence of the peak in the wrong sign BK
- no “bump” in Monte Carlo spectrum from B** decays

Λ_b lifetime from CDF

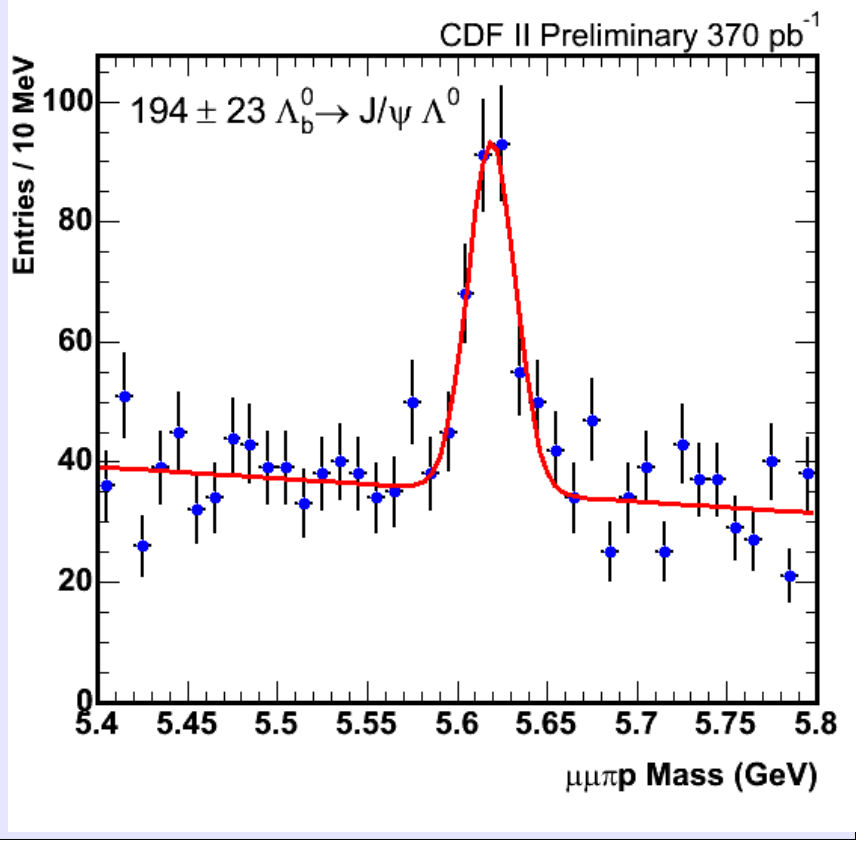
The lightest b baryon: (udb), rich physics program

Lifetime measurements allow to test Heavy Quark Expansion

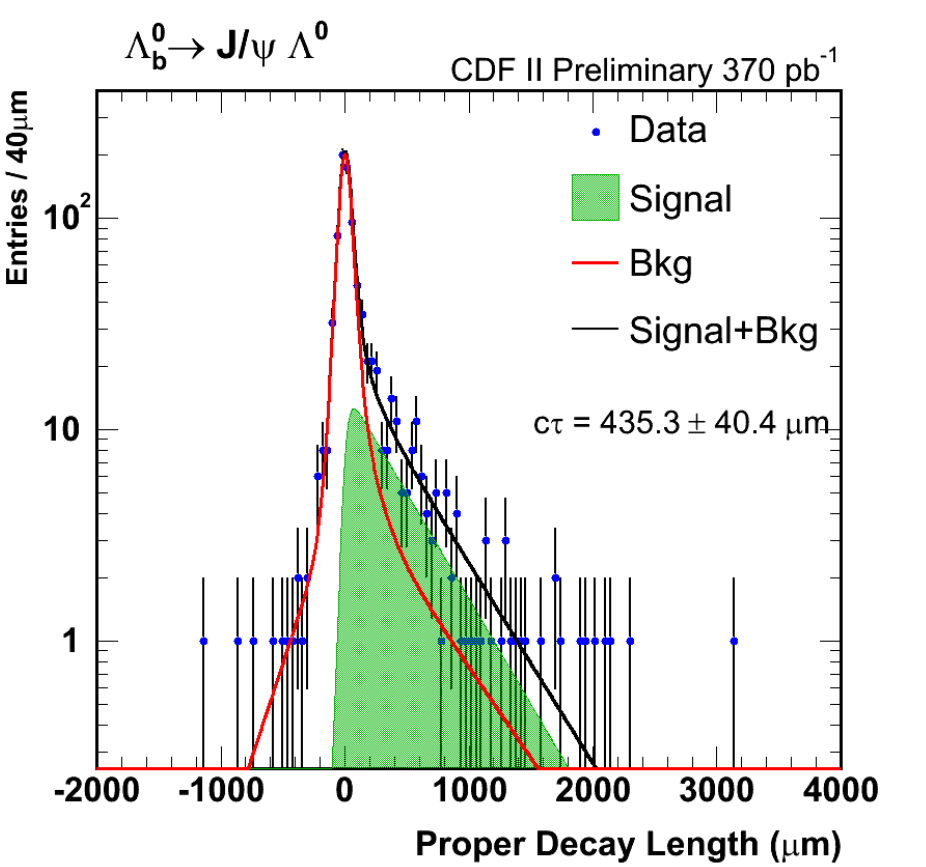
CDF measures Λ_b lifetime in fully reconstructed $\Lambda_b \to J/\psi\, \Lambda$

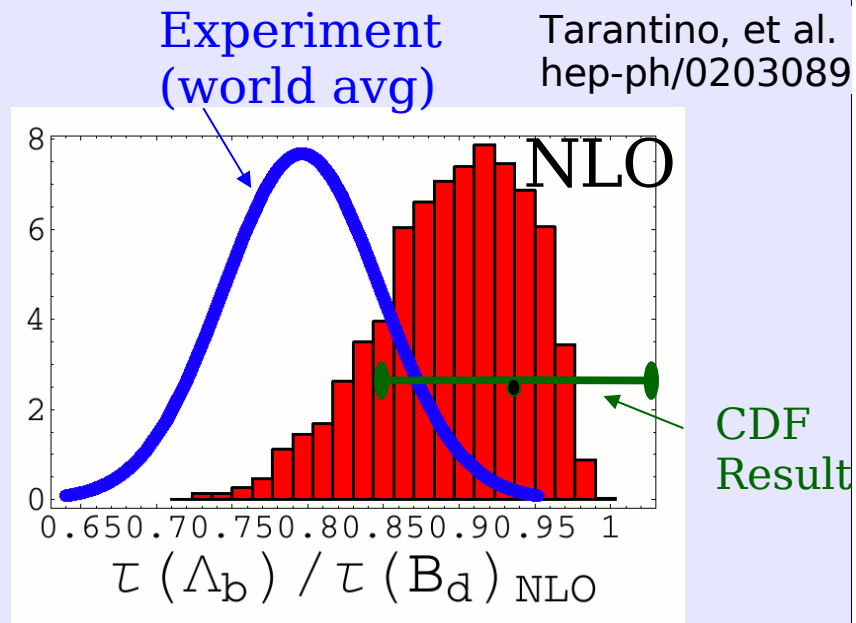
- better τ resolution wrt semileptonics
- largest fully reconstructed sample of Λ_b in the world

Cross-checked on $B \to J/\psi K_s$ (same topology)



Λ_b lifetime: results





Tarantino, et al.
hep-ph/0203089

- CDF new result sits in the theory preferred region
- more experimental inputs are desirable

CDF (370pb-1):

$$\tau(\Lambda_b) = 1.45^{+0.14}_{-0.13}(stat) \pm 0.02(syst)\, ps$$

expect updated result with > x2 statistics

Summary

Precision measurements of b and c properties

- many unique to Tevatron

While this talk is restricted spectroscopy, check out other talks from CDF and D0 with new exciting results on heavy flavor

Good times for heavy flavor physics at Tevatron: >1 fb^{-1} of data

Dummy Slide