Heavy Flavor Spectroscopy at the Tevatron

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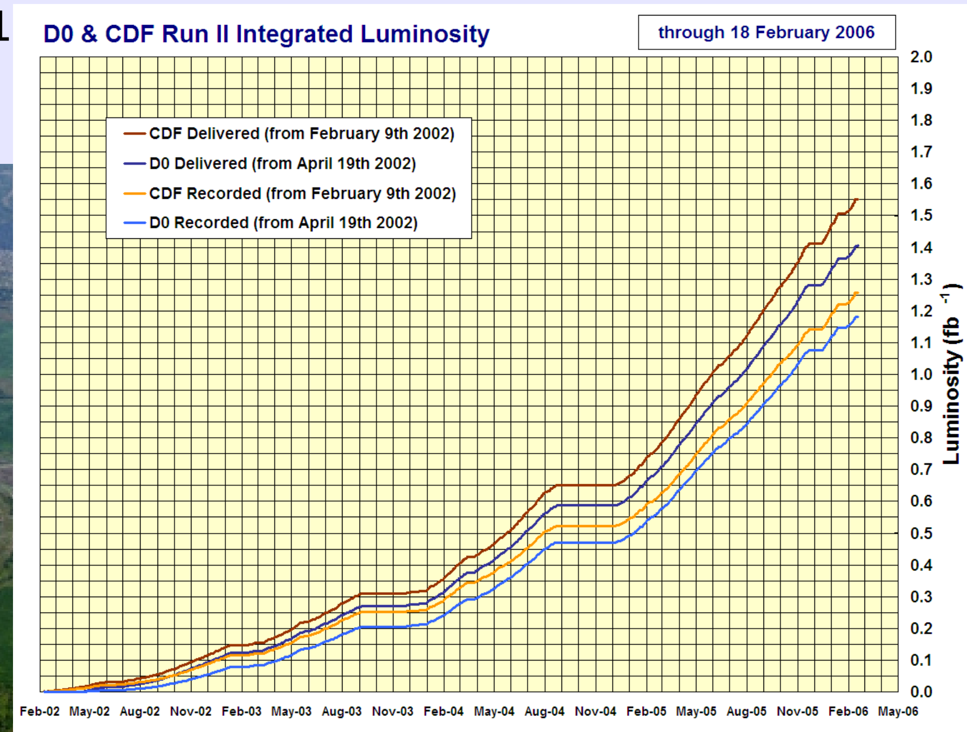
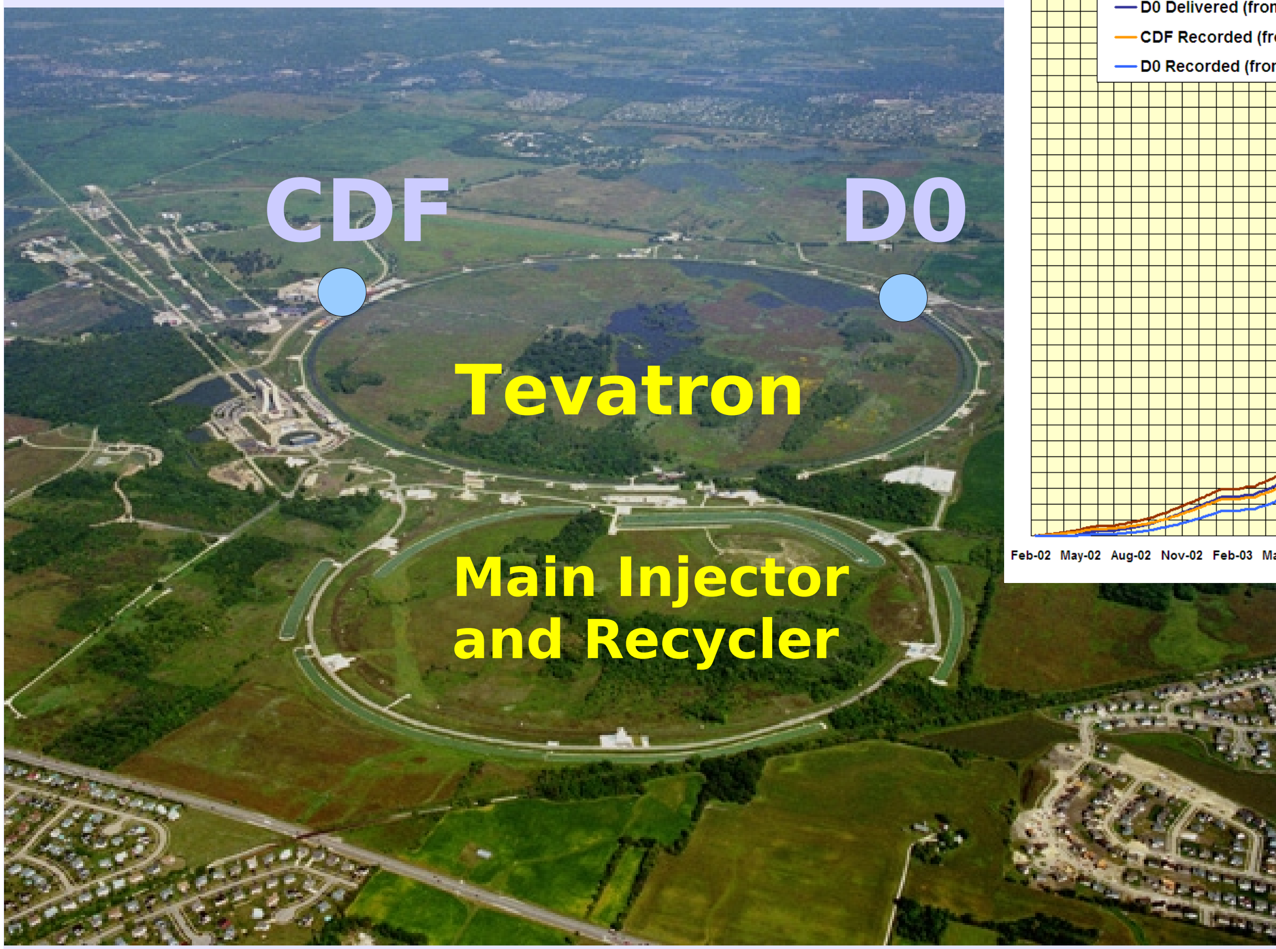
Topics

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

Tevatron

- machine delievered >1.5 fb^{-1}
- CDF and D0 recorded >1.2 fb^{-1} each
- analyses use 0.2 to 1.0 fb^{-1}





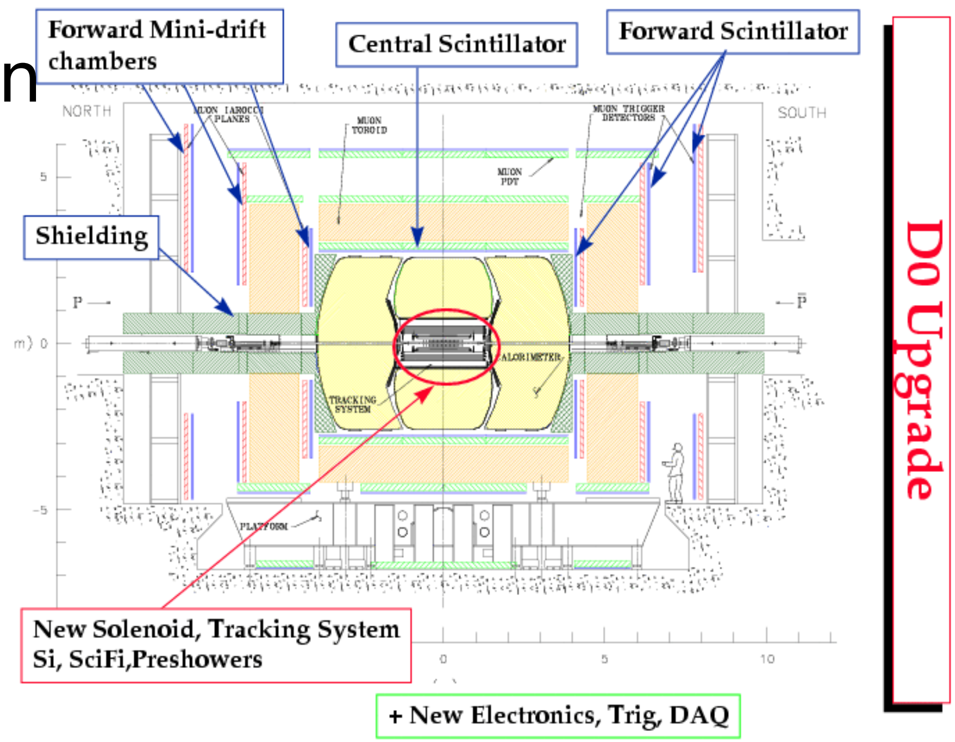
$p\bar{p}$ collisions

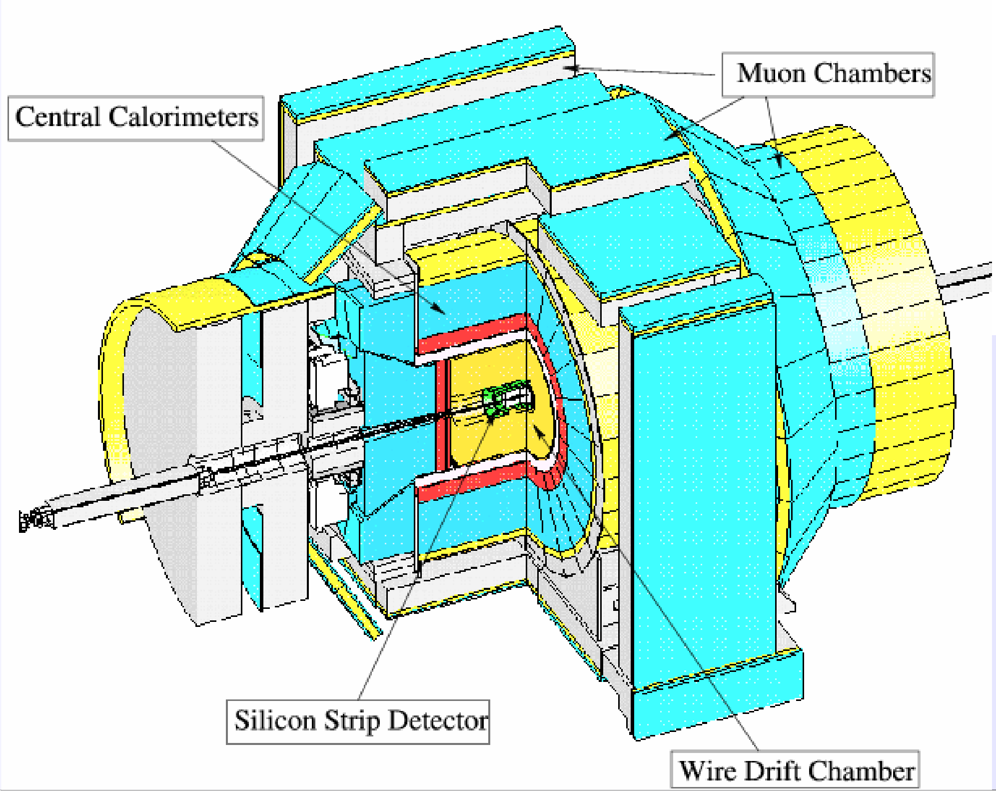
CM 1.96 TeV

CDF and D0 Experiments

CDF:

- great **m**, imp.par. resolution
- displaced track triggers
- triggered μ to |η|<1.1
- particle ID with dEdx, ToF

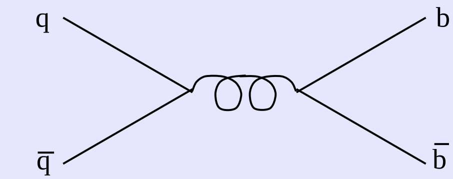




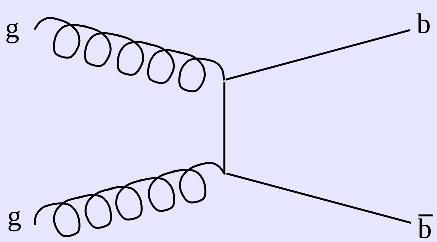
D0:

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

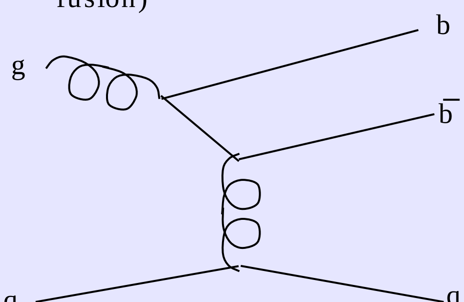
Heavy Flavor Physics at Tevatron



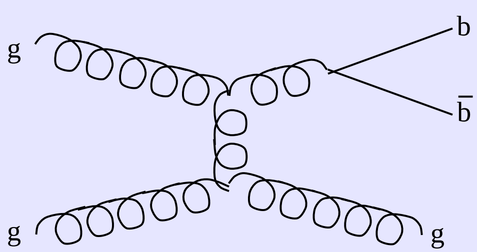
Flavor Creation (annihilation)



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

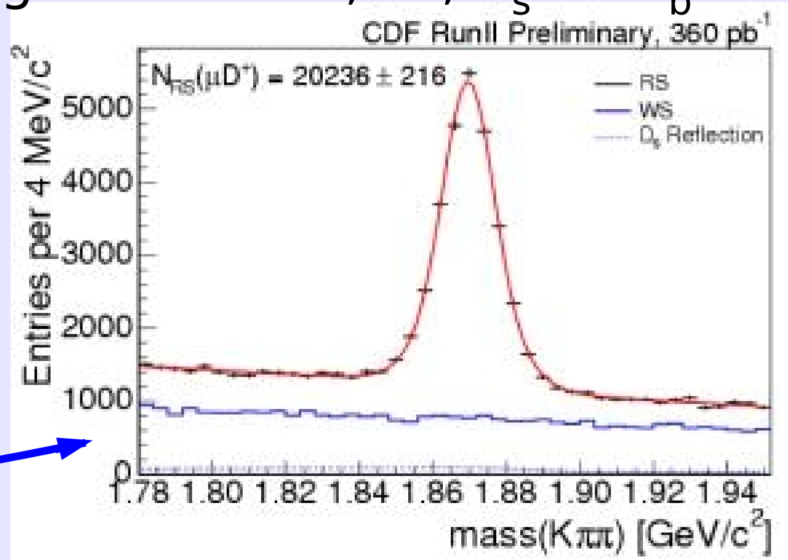
b Hadron Production Fractions

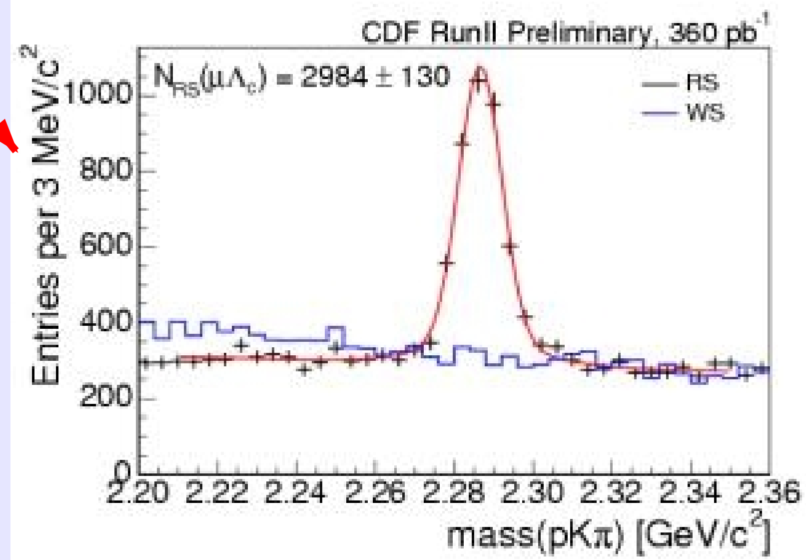
Rate of b quark fragmentation to form mesons and baryons:

- f_u, f_d, f_s and $f_{\Lambda b}$ – probabilities that b fragments to B^0, B^+, B_s or Λ_b
- non-perturbative: has to be measured
- interesting to compare e^+e^-(LEP) with $p\bar{p}$(Tevatron)

CDF reconstructs final states:

$$l^- D^0 \quad l^- D^+ \quad l^- D^{*+} \quad l^- D_s^+ \quad l^- \Lambda_c^+$$





Sample composition:

- different B mesons – same final states
- cross-talk via excited states, disengangled

Particle ID likelihood cuts (dE/dx):

➔ important to clean up the Λ_c signal

b Hadron Fractions: results

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

- relative fractions f_u/f_d , $f_s/(f_u+f_d)$ and $f_{\Lambda b}/(f_u+f_d)$ (reduce sytematics)

$$\frac{f_s}{f_u+f_d} \times \mathcal{BR}(D_s^+ \to \phi\pi^+) = (5.76 \pm 0.18(stat)^{+0.45}_{-0.42}(sys)) \times 10^{-3}$$

$$\frac{f_{\Lambda_b}}{f_u+f_d} \times \mathcal{BR}(\Lambda_c^+ \to pK^-\pi^+) = (14.1 \pm 0.6(stat)^{+5.3}_{-4.4}(sys)) \times 10^{-3}$$

$$\frac{f_{\Lambda_b}}{f_u+f_d} \times \mathcal{BR}(\Lambda_b^0 \to \ell\nu\Lambda_c^+)\mathcal{BR}(\Lambda_c^+ \to pK^-\pi^+) = (12.9 \pm 0.6(stat) \pm 3.4(sys)) \times 10^{-4}$$

Using World's best Br available, CDF derives:

$$\frac{f_u}{f_d} = 1.054 \pm 0.018(stat)^{+0.025}_{-0.045}(sys) \pm 0.082(\mathcal{BR})$$

$$\frac{f_s}{f_u+f_d} = 0.160 \pm 0.005(stat)^{+0.011}_{-0.010}(sys)^{+0.057}_{-0.034}(\mathcal{BR})$$

$$\frac{f_{\Lambda_b}}{f_u+f_d} = 0.281 \pm 0.012(stat)^{+0.058}_{-0.056}(sys)^{+0.128}_{-0.086}(\mathcal{BR}).$$

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

The mystery of X(3872)

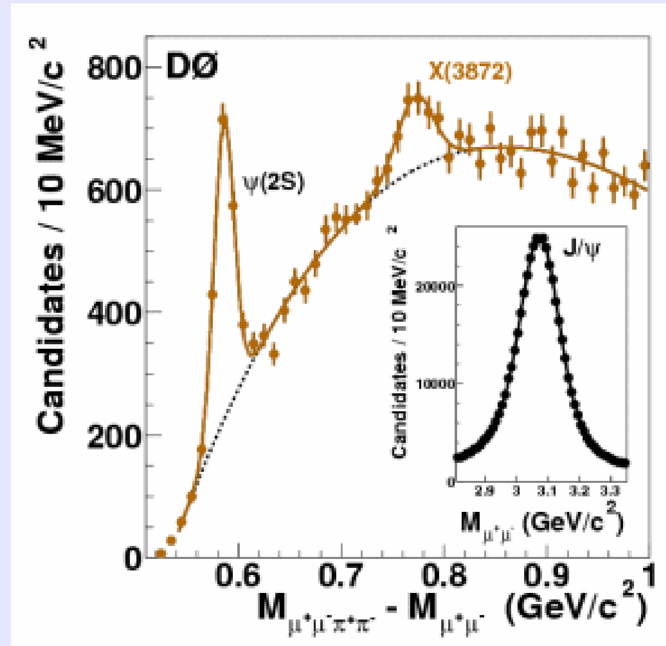
Aug'03: Belle annonunces discovery of $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

What is it? Pros/cons for any explanation

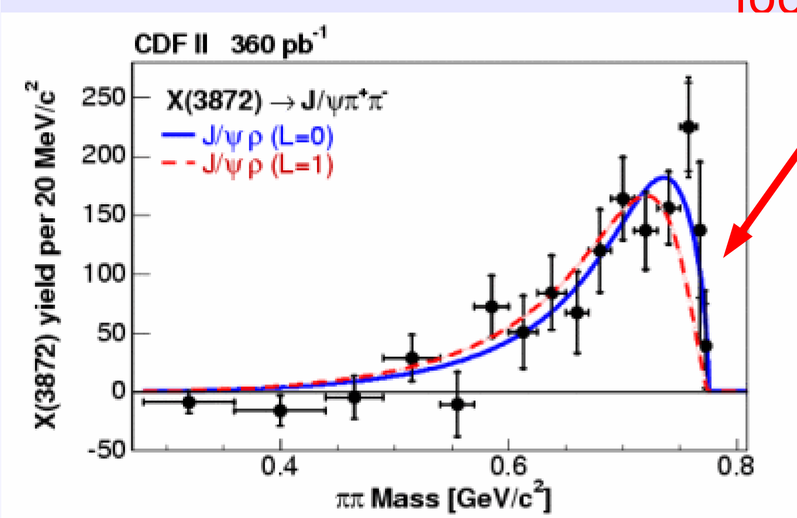
- DD* molecule?
- Excited ccbar state

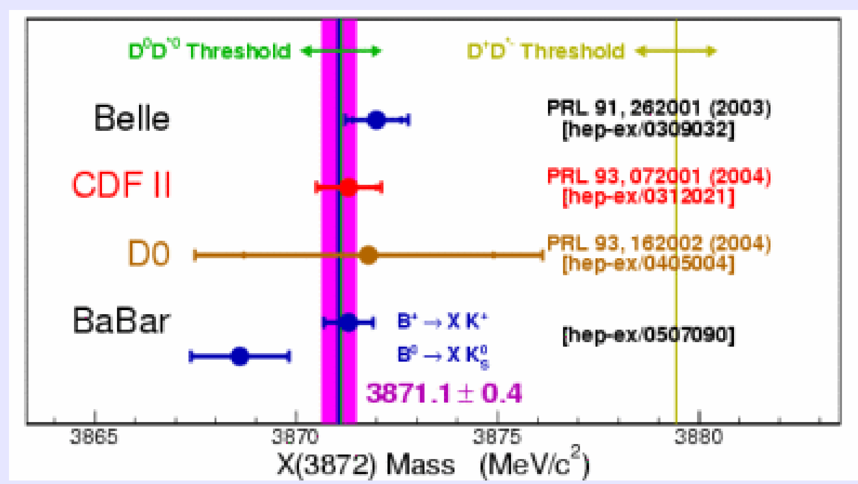
Results from CDF and D0 rapidly follow

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



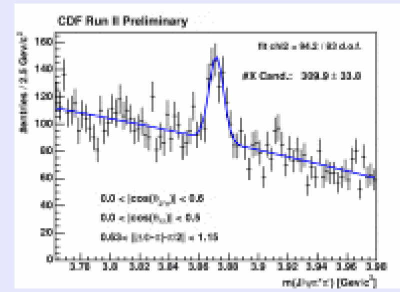
looks like J/Ψ ρ





X(3872): angular analysis

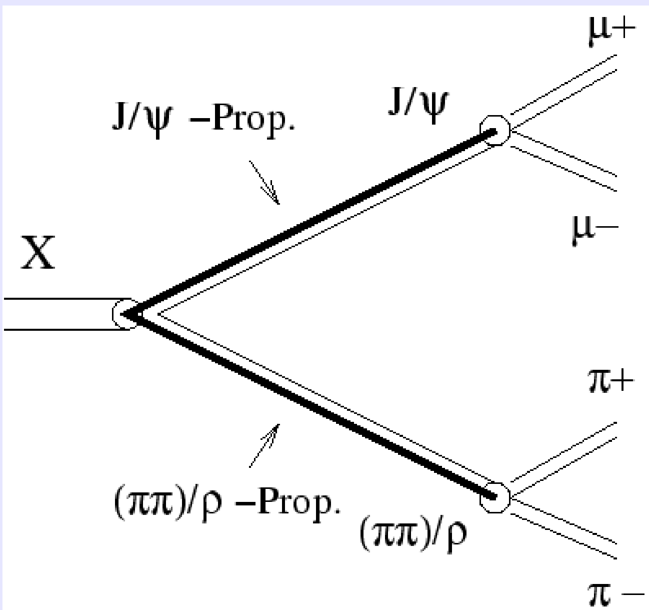
Example:



CDF seeks to determine J^{PC} of the X(3872)

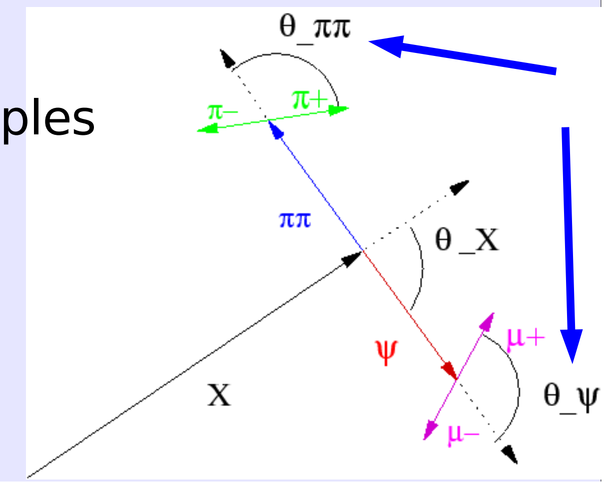
a sample of ~3000 of X(3872) candidates with 780 pb^{-1} of data

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

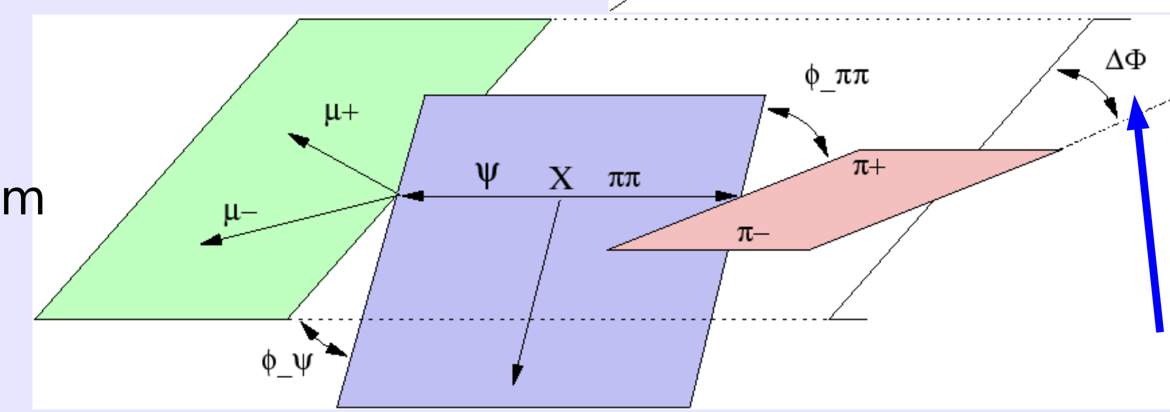


Fit m(X) in 3x2x2 subsamples

- 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



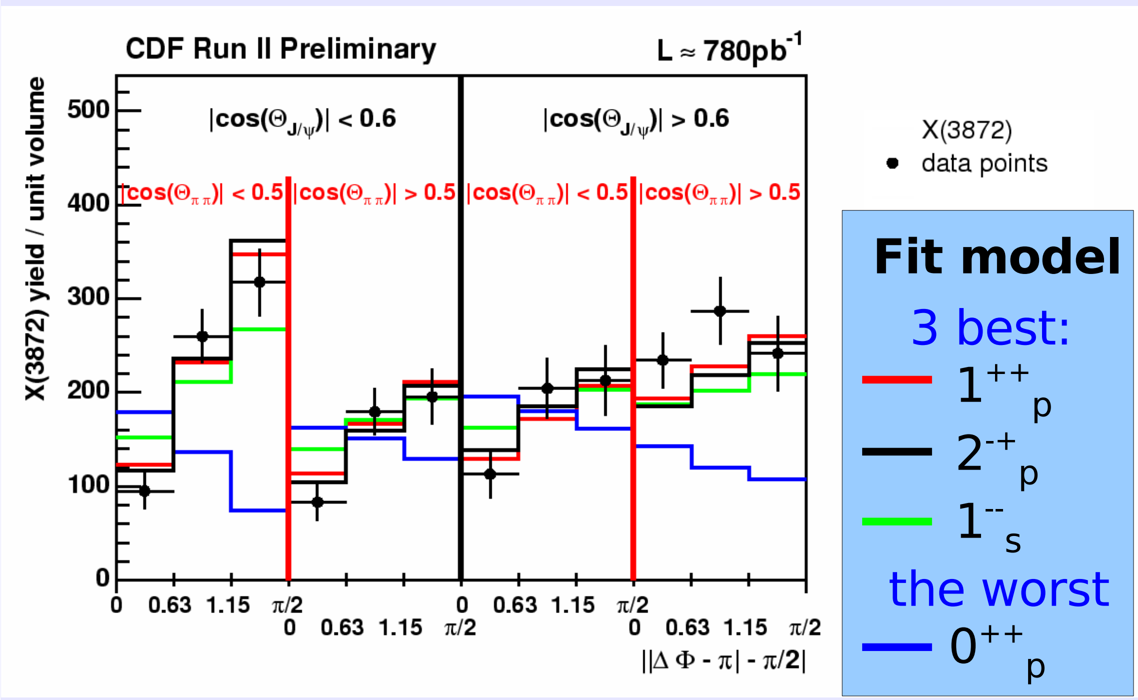
X(3872): results for J^{PC}

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	$5.5 \cdot 10^{-5}$
1^{+-}	39.8	$3.8 \cdot 10^{-5}$
2^{--}	39.8	$3.8 \cdot 10^{-5}$
3^{+-}	39.8	$3.8 \cdot 10^{-5}$
3^{--}	41.0	$2.4 \cdot 10^{-5}$
2^{++}	43.0	$1.1 \cdot 10^{-5}$
1^{-+}	45.4	$4.1 \cdot 10^{-6}$
0^{-+}	103.6	$3.5 \cdot 10^{-17}$
0^{+-}	129.2	$\lesssim 1 \cdot 10^{-20}$
0^{++}	163.1	$\lesssim 1 \cdot 10^{-20}$



Result:

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

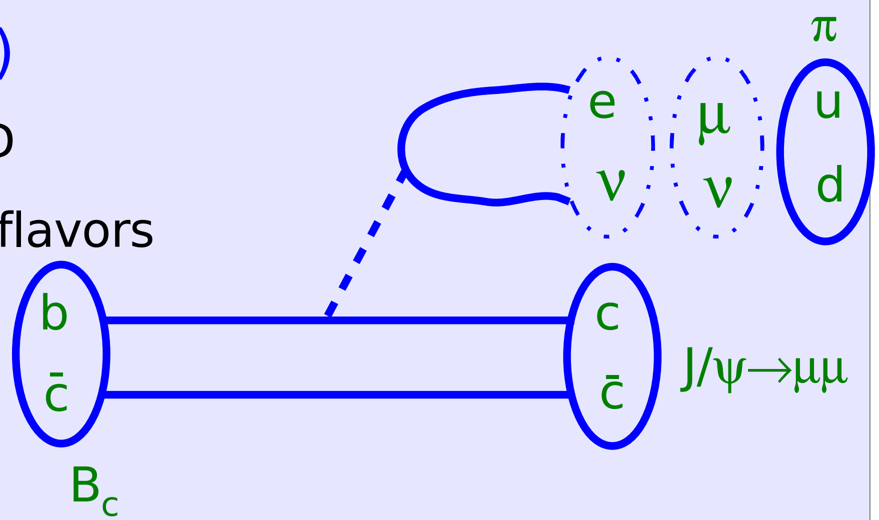
Cross-check on Ψ(2S):

- same final state, J^{PC} reproduced

B_c: introduction

Bound state of two heavy quarks ($b\bar{c}$)

- good lab for potential models, lattice QCD
- B_c – the only meson with different heavy 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:Λ_b≈40:40:10:10, B_c~0.5%
- short lifetime ⇒difficult selection

B_c: observation and mass

We reconstruct B_c in 3 channels:

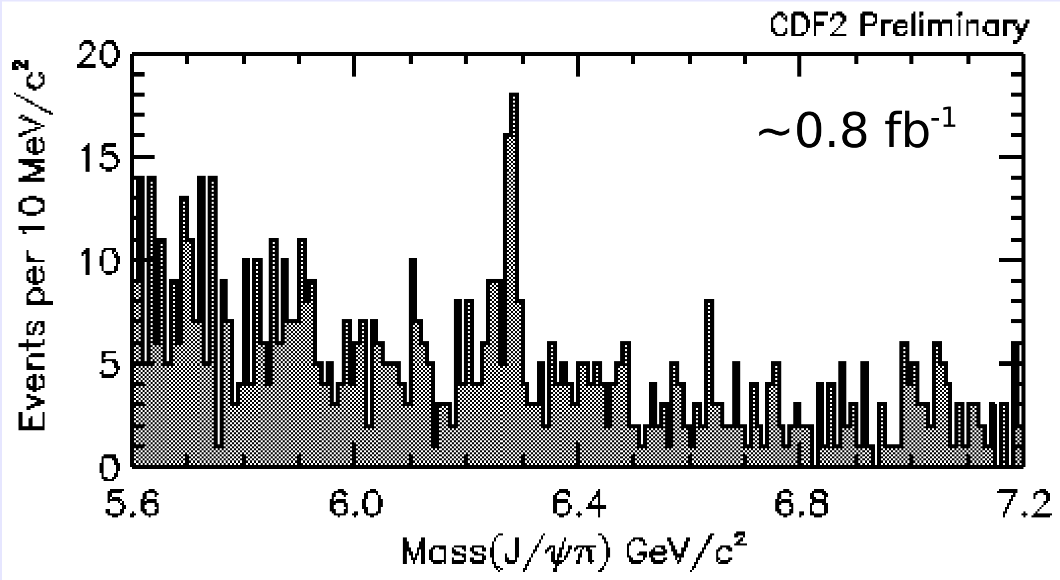
$B_c \to J/\psi\, e\, \nu$ CDF
$B_c \to J/\psi\, \mu\, \nu$ CDF, D0
} semileptonics: good for lifetime (sufficient yields)

$B_c \to J/\psi\, \pi$ CDF
} hadronic decays: good for mass (fully reconstructed)

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

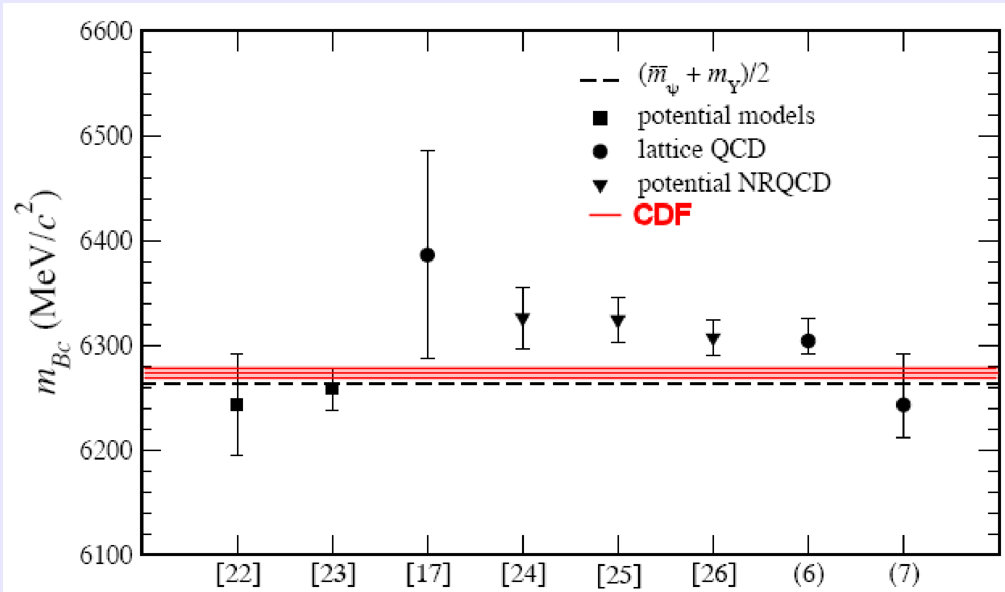
CDF: fully reconstructed $B_c \to J/\Psi\pi$ sample for mass measurements

$M(B_c) = 6275.2 \pm 4.3 \pm 2.3$ MeV/c^2



B_c: lattice results vs CDF

Lattice calculations show moderately good agreement with the CDF measurement of the B_c mass



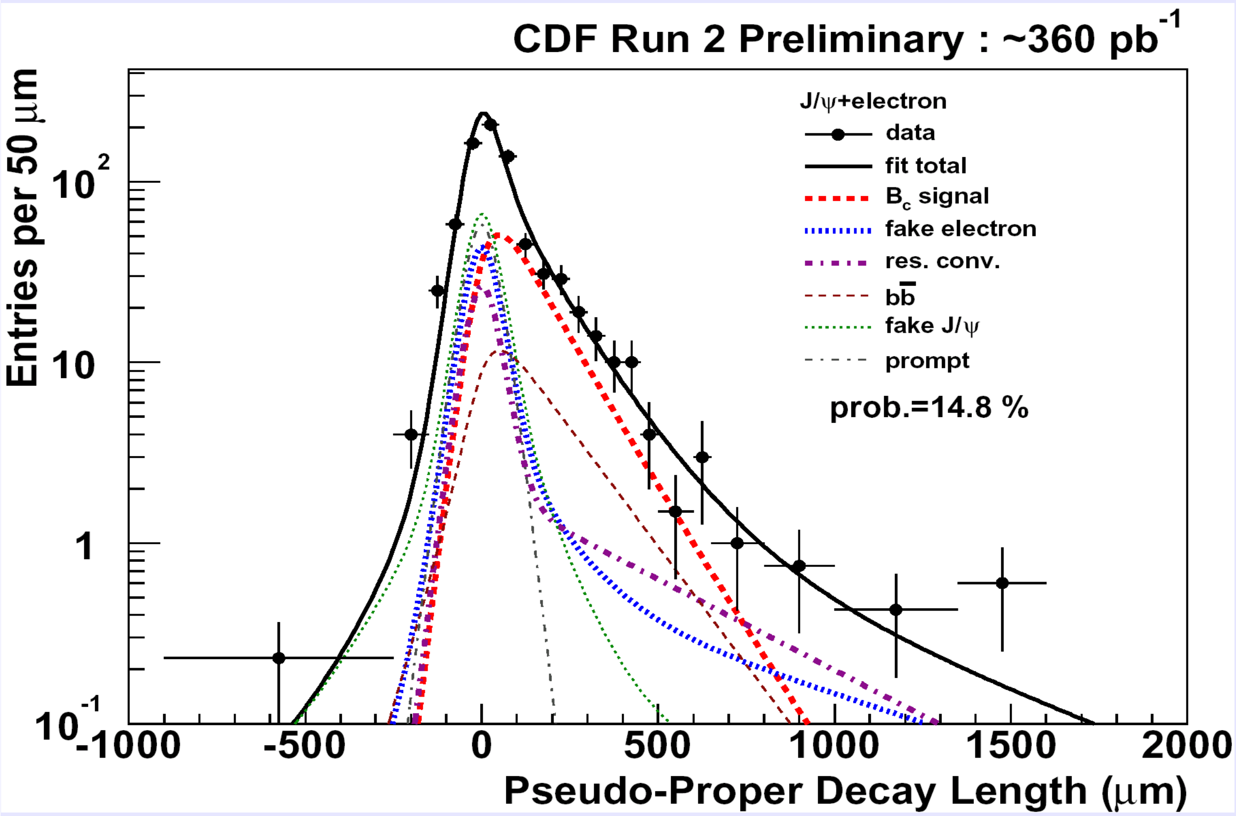
theory:
PRL 94, 1720001 (2005)

$M(B_c)_{CDF} = 6275.2 \pm 4.3 \pm 2.3$ MeV/c²

$M(B_c)_{LAT} = 6304 \pm 12^{+18}_{-0}$ MeV/c²

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

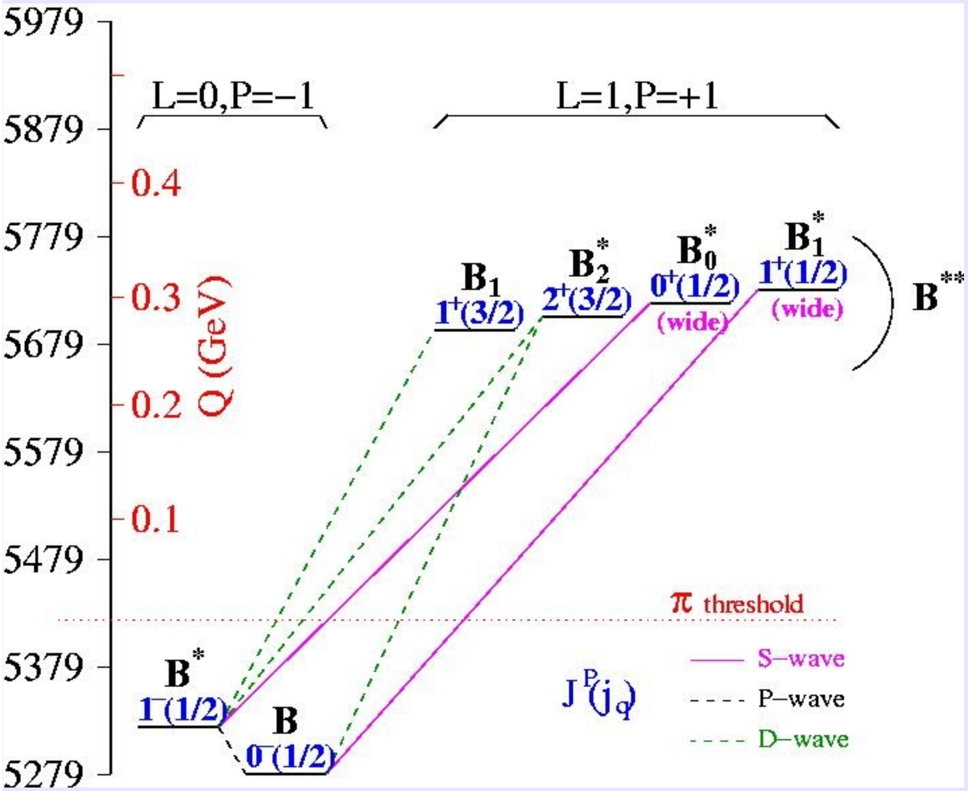
CDF: lifetime measured in J/Ψe channel: $0.474^{+0.073}_{-0.066} \pm 0.033$ ps on 360 pb^{-1}

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 $(b\bar{q})$ system



Qualitative picture well understood:

- 4 P-wave 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

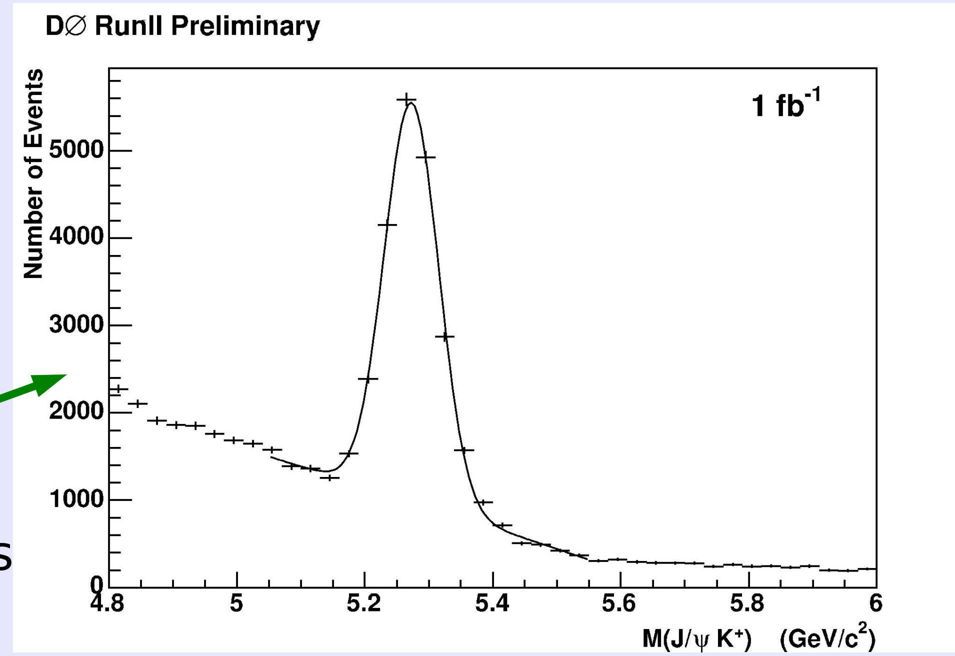
B** narrow states from D0

Decay channels: find $B^{**} \rightarrow B^{(*)}\pi^-$ 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 $B^+ \rightarrow J/\psi\ K^+$ candidates
- photon in $B^* \rightarrow \gamma B$ not reconstructed

Add events from all 3 modes, fit mass difference $M(B\pi) - M(B)$

Constrained:

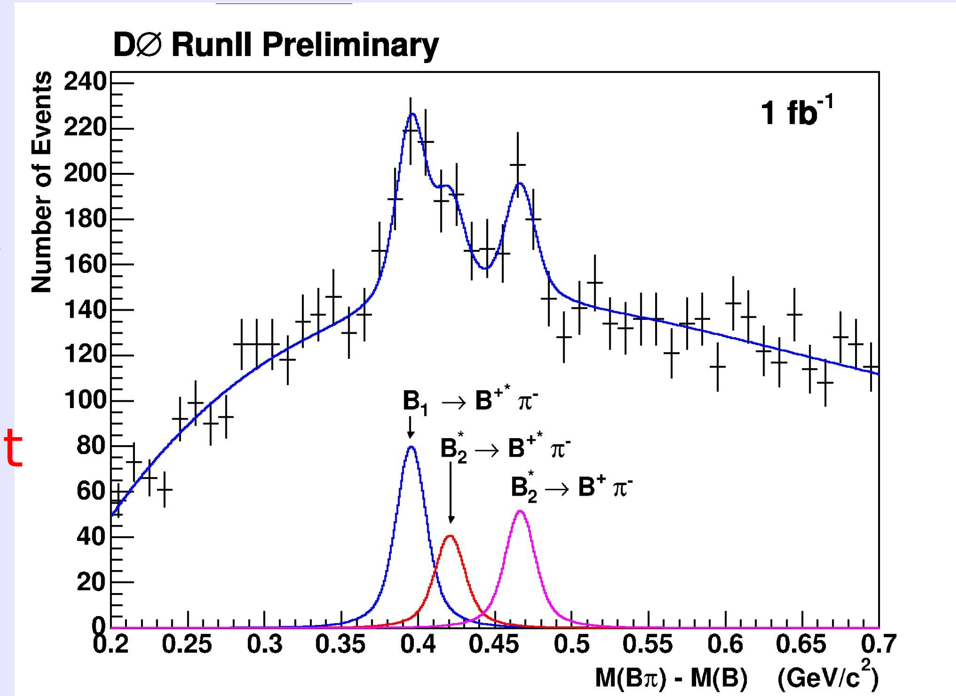
- $\Gamma(B_1) = \Gamma(B_2^*) = \Gamma$ from theoretical expectations (Γ floats)
- also, $M(B^*)-M(B^+)=45.78$ MeV/c^2 [PDG]

B**: results from D0

First observation of separate peaks

$M(B_1) = 5720.8 \pm 2.5 \pm 5.3$ 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

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

Production rates:

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

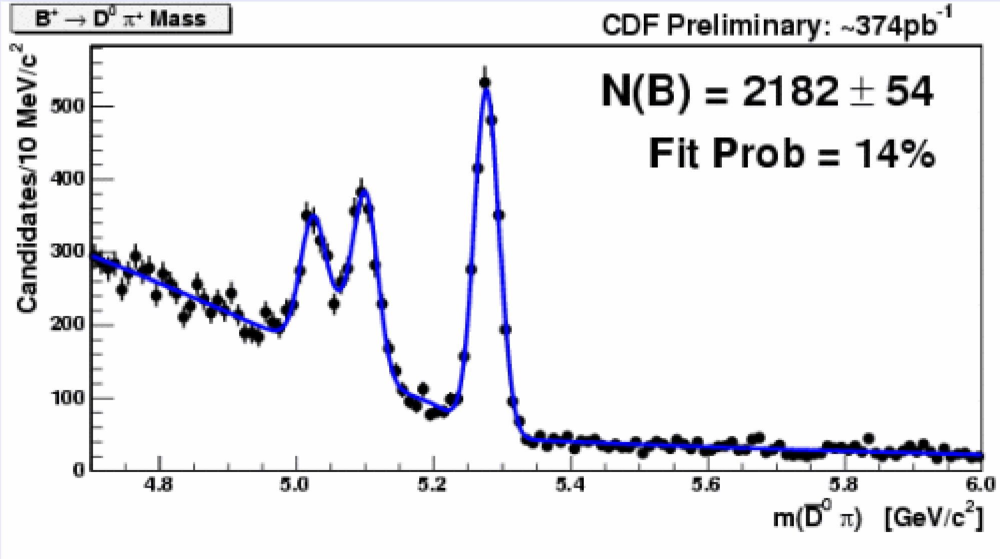
$$\frac{BR(B_2^* \to B^*\pi)}{BR(B_2^* \to B^{(*)}\pi)} = 0.513 \pm 0.092 \pm 0.115$$

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

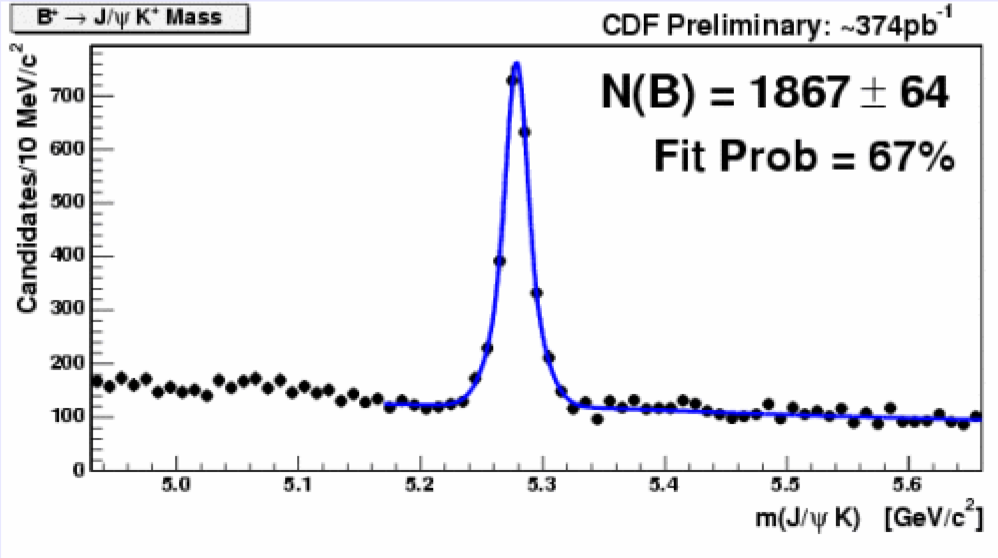
B** narrow states from CDF

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

- B^+ decay: $B^+ \to J/\psi\, K^+$
- and $B^+ \to D^0\pi^+$



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



D* background to $D^0\pi^+$ is suppressed in selection

B**: results from CDF

Fit $M(B\pi)–M(B)–M(\pi)$ simultaneously for all channels

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

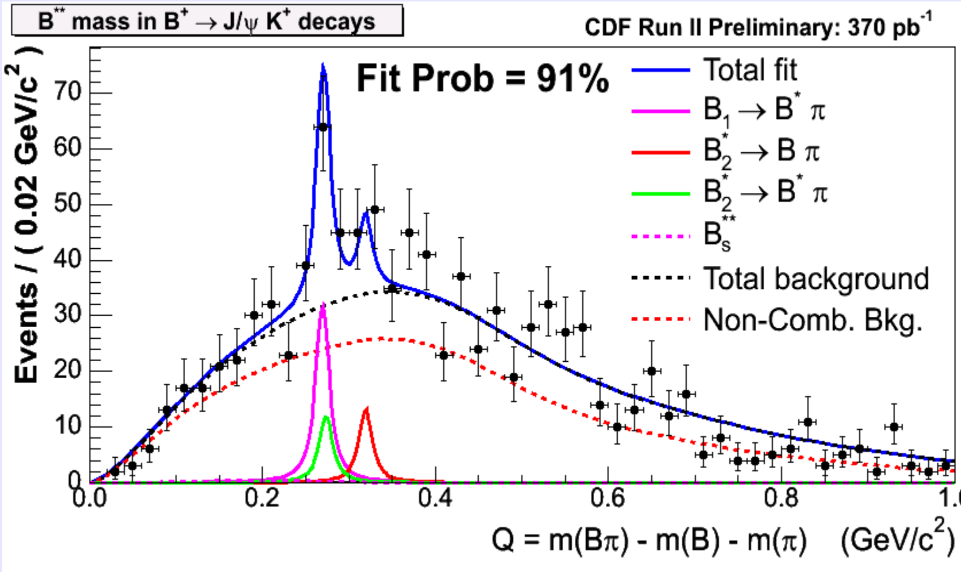
- also, fix $\Gamma(B_1^0) = \Gamma(B_2^{*0})$

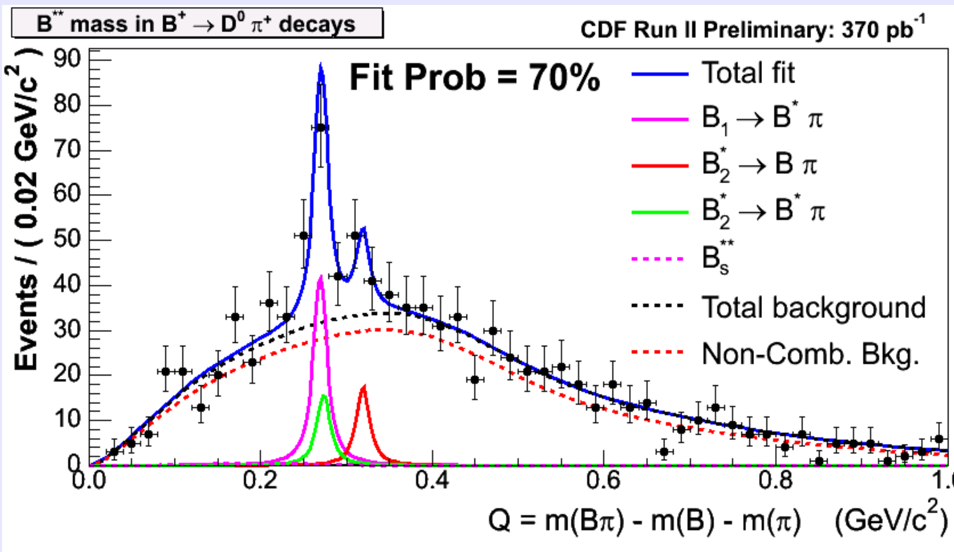
Fix $\frac{Br(B_2^{*0} \to B^*\pi)}{Br(B_2^{*0} \to B\pi)} = 1.1 \pm 0.3$ Delphi 2004-025 conf 700

Precise mass measurements:

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

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





Search for B^*_{s2} at D0

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

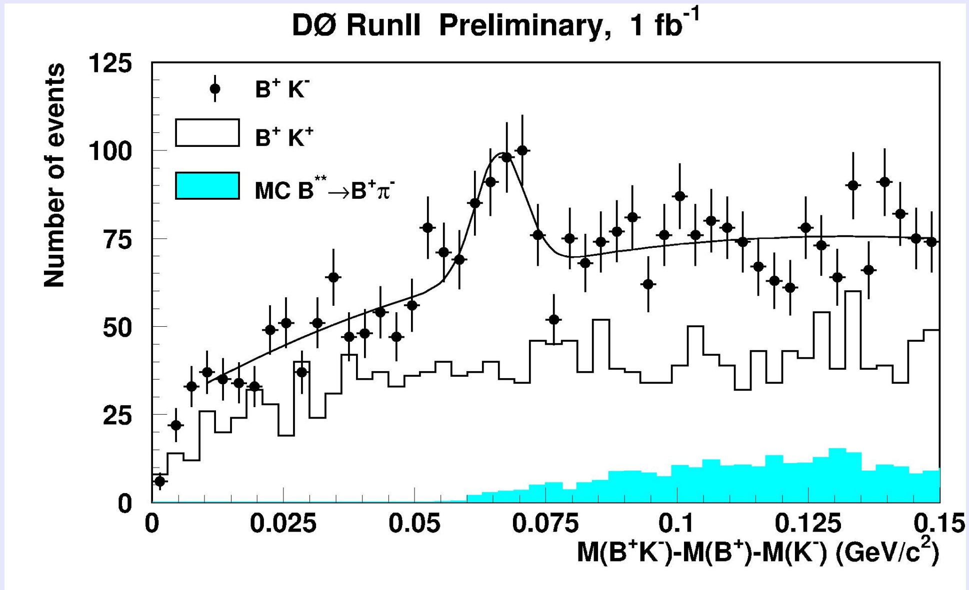
- wide states B^*_{s0} and B^*_{s1}
- narrow states B_{s1} and B^*_{s2}
- even less well studied than B**

The signature:

- due to isospin conservation decays to $B_s\pi$ highly suppressed
- search for excited states decaying to B^+K^-
- use the same $B^+ \rightarrow J/\psi\ K^+$ 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 $>5\sigma$!

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

Checks:

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

Summary

Precision measurements of b and c properties

- CDF narrowed J^{PC} of X(3872) to 2 possibilities!
- B** states (d and s) are now being resolved

  and precisely measured!
- B_c mass is now well measured!

Good times for heavy flavor physics at Tevatron: on the way to collecting multi-fb^{-1} of data

While this talk is restricted spectroscopy, check out

other talks from CDF and D0 with new exciting

results on heavy flavor