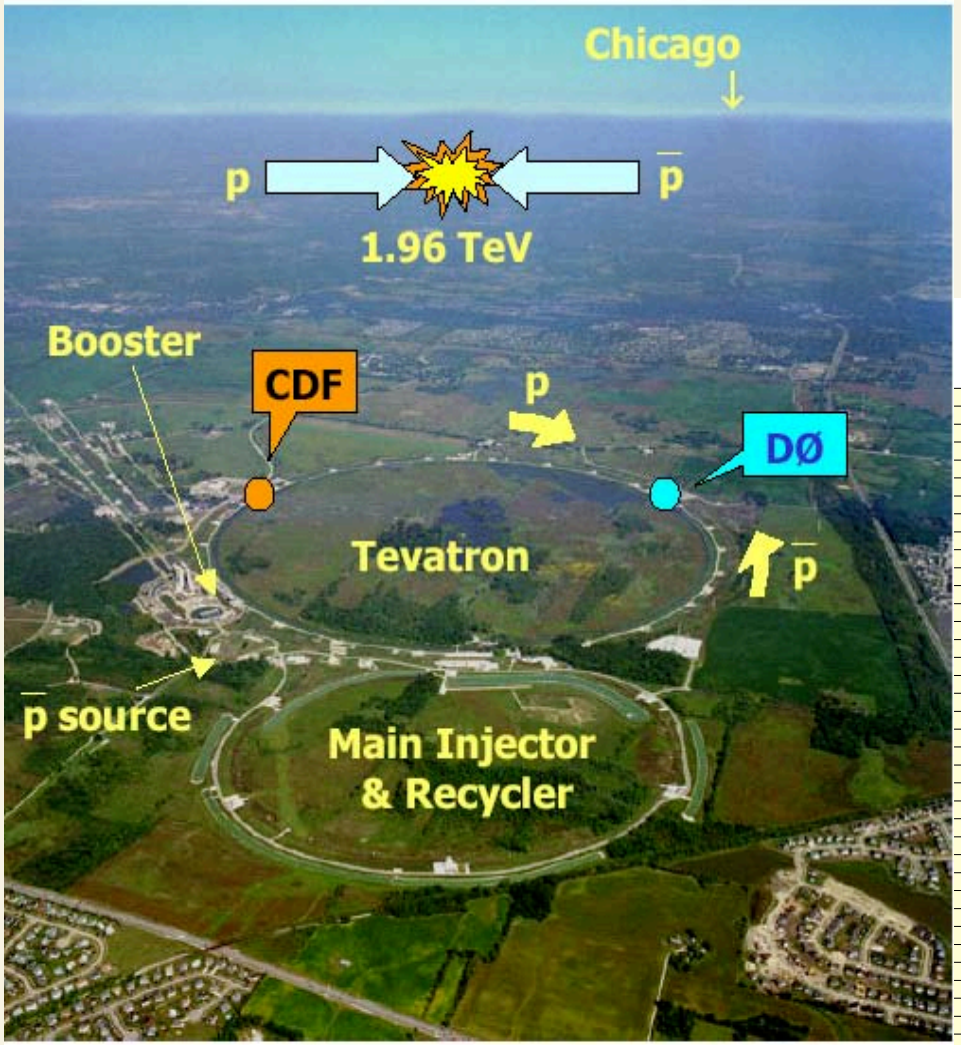
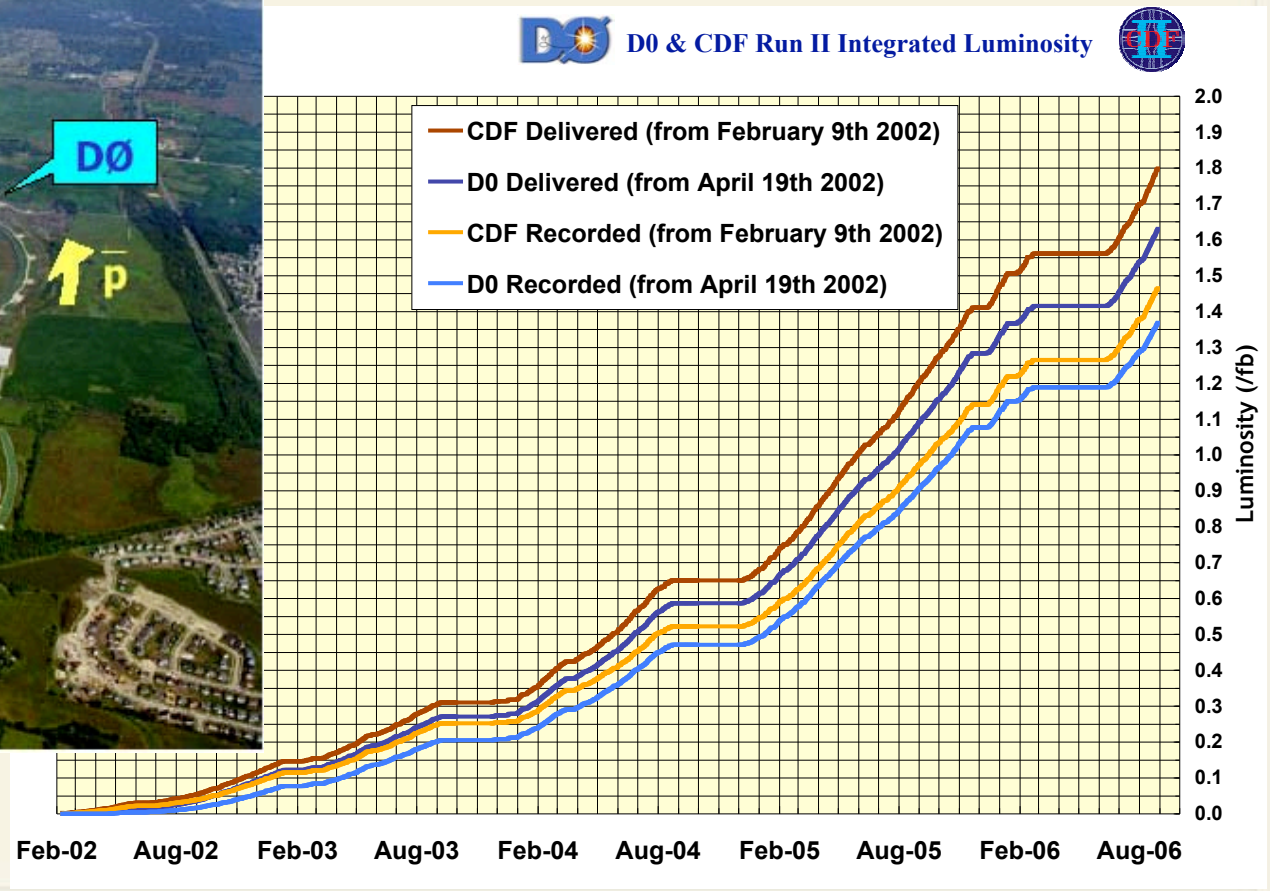
B_c and Excited B States Tevatron Review

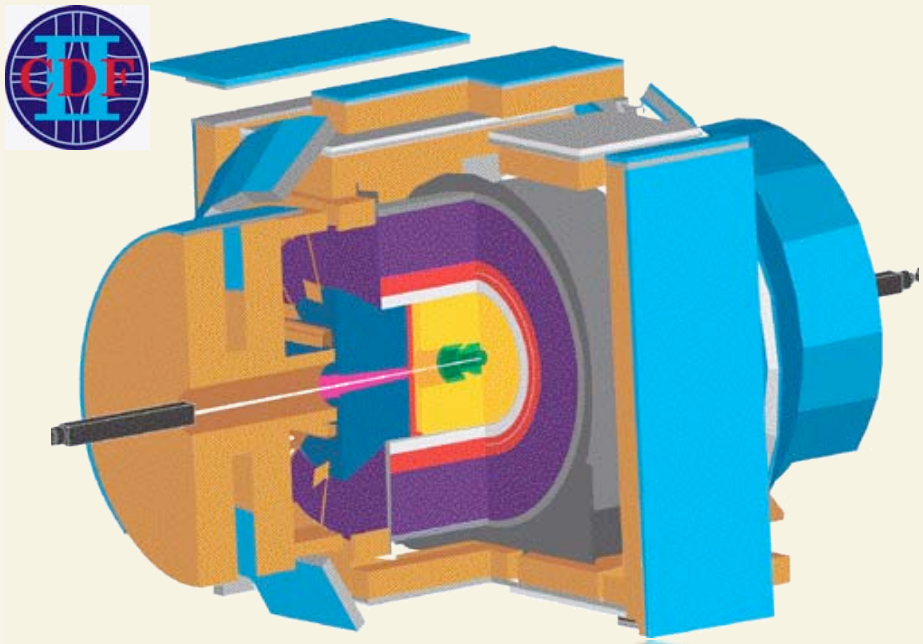
Remigius K Mommsen
University of Manchester / Fermilab

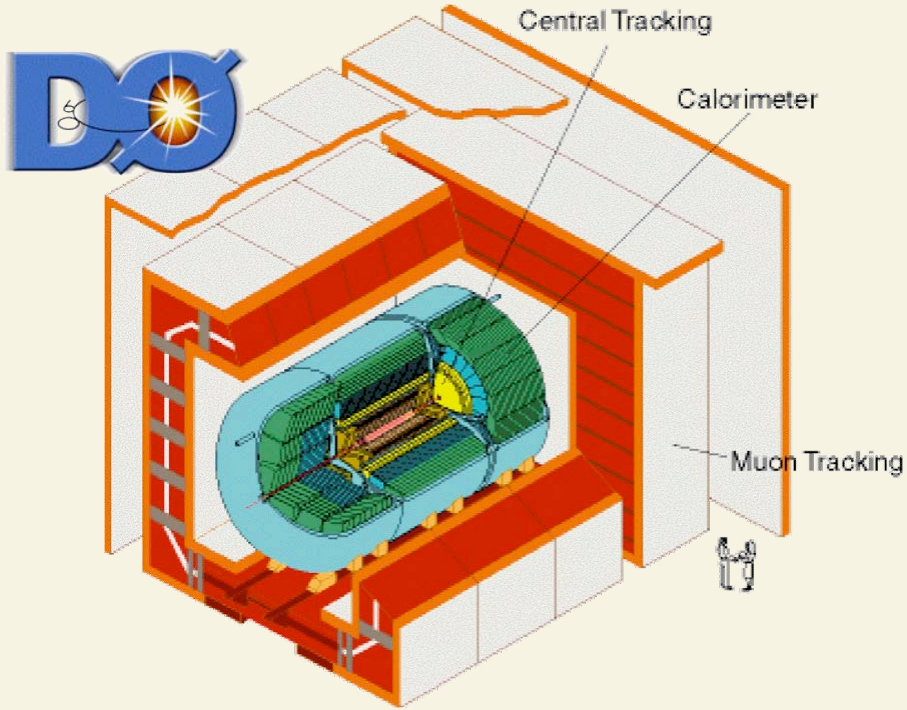
Tevatron


Chicago
p
p̄
1.96 TeV
Booster
CDF
p
DØ
Tevatron
p̄
p̄ source
Main Injector
& Recycler


D0 & CDF Run II Integrated Luminosity
CDF Delivered (from February 9th 2002)
D0 Delivered (from April 19th 2002)
CDF Recorded (from February 9th 2002)
D0 Recorded (from April 19th 2002)
Luminosity (/fb)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Feb-02
Aug-02
Feb-03
Aug-03
Feb-04
Aug-04
Feb-05
Aug-05
Feb-06
Aug-06

Detectors



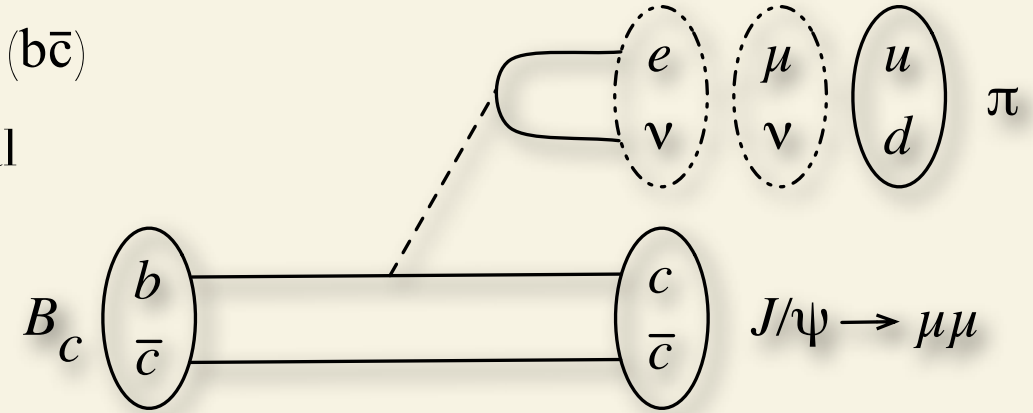


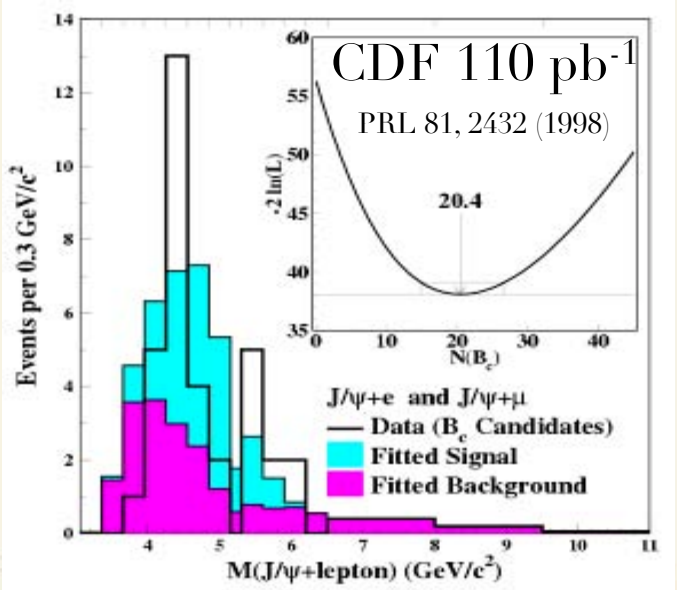
- good impact parameter resolution
- displaced track triggers
- μ trigger to $|\eta| < 1.1$
- particle ID with dE/dx, ToF

- μ trigger to $|\eta| < 2.0$
- track trigger to $|\eta| < 1.7$
- high μ purity
- good electron ID

B_c: Introduction

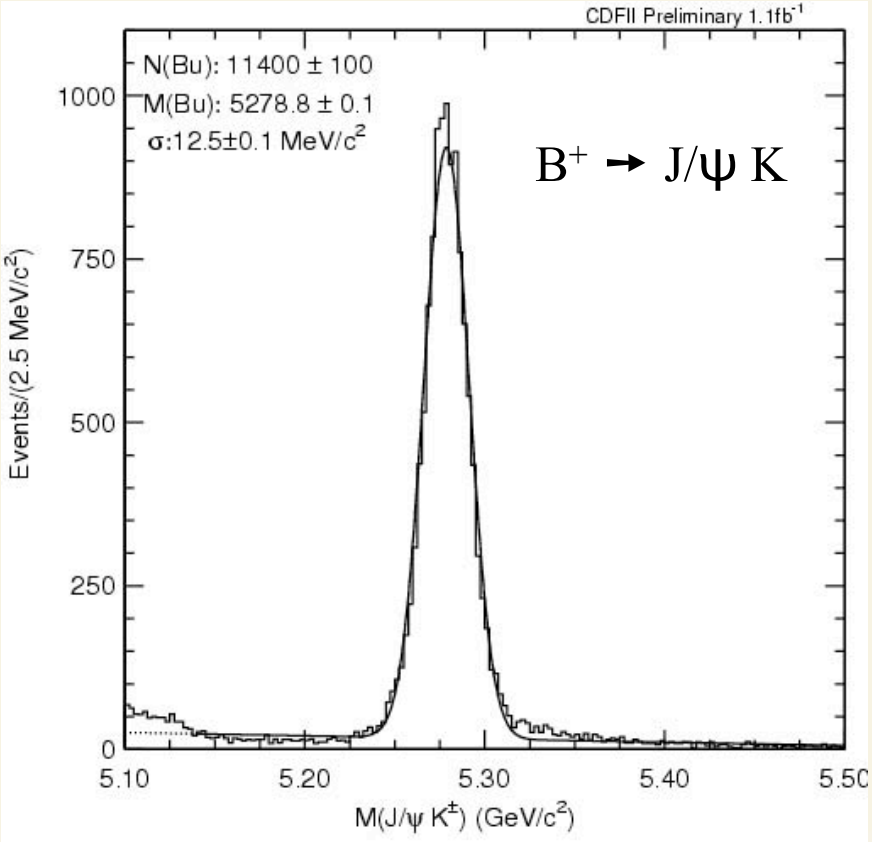
- Bound state of two heavy quarks ($b\bar{c}$)
  - good lab for phenomenological models, lattice QCD
  - only weak decays possible
- Experimentally challenging
  - Low production rate ~0.5% of total B production rate
  - Short lifetime makes selection difficult
- First observation by CDF in 1998, but large uncertainties due to statistics
- Tevatron run II yields much higher statistics
  - exclusive states allow for mass measurements
  - more precise lifetime measurements



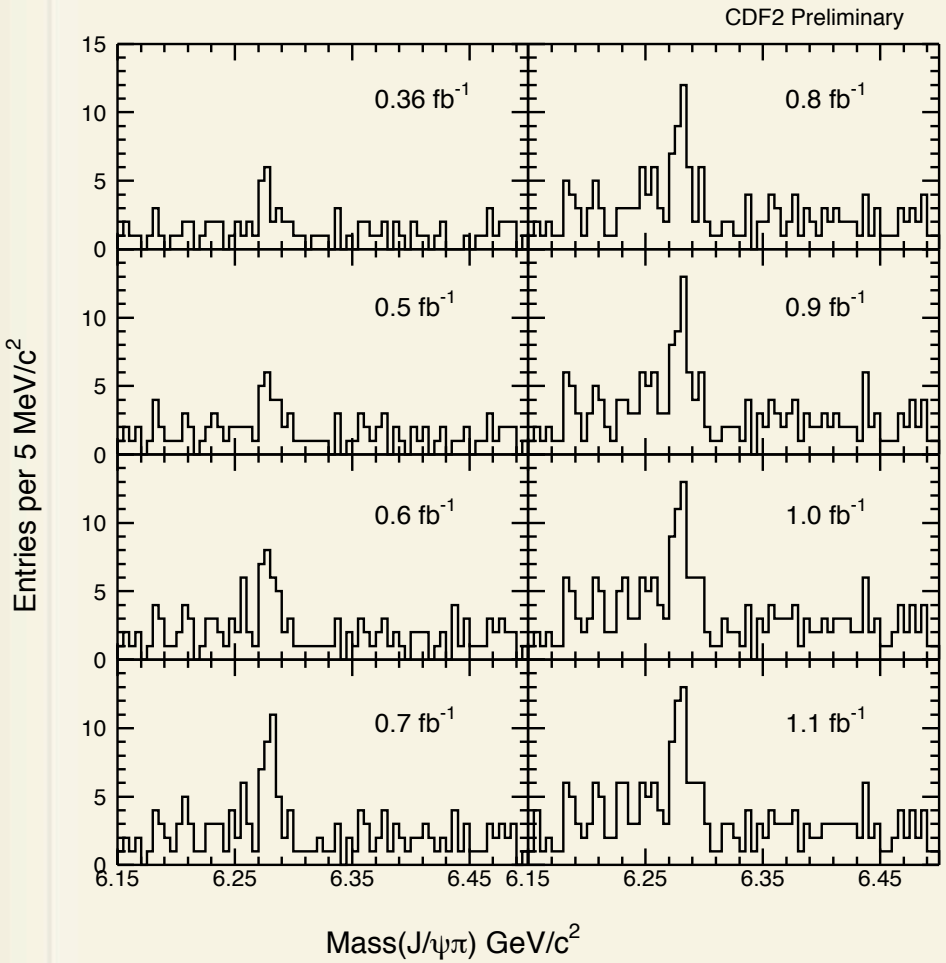


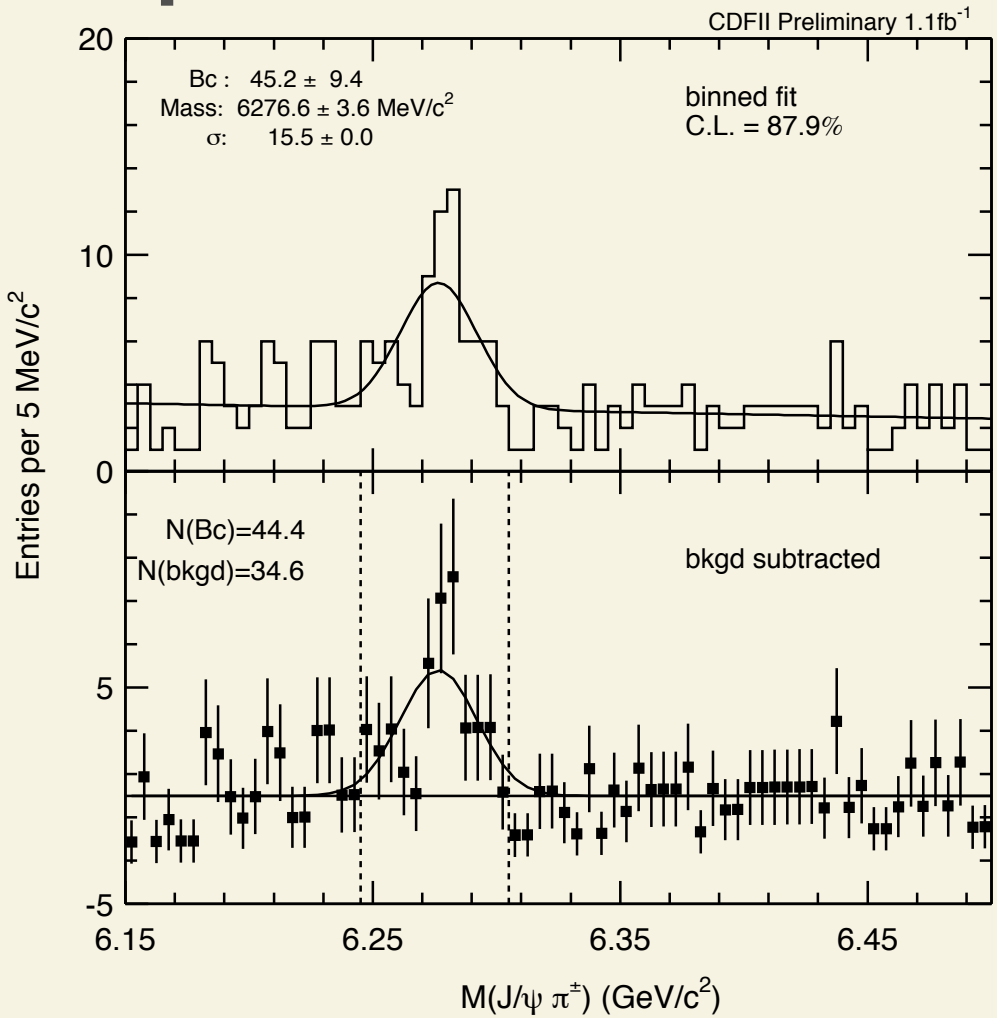
$B_c \rightarrow J/\psi\ \pi$: Reference Decay $B^+ \rightarrow J/\psi\ K$

- Fully reconstructed hadronic decay allows for precise mass measurement
- New analysis from CDF using 1.1 fb^{-1}
- Tune selection on well understood reference decay $B^+ \rightarrow J/\psi\ K$
- After finalizing the selection, replace K by π
- Wait for a significant excess of events
- Measure properties of B_c



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



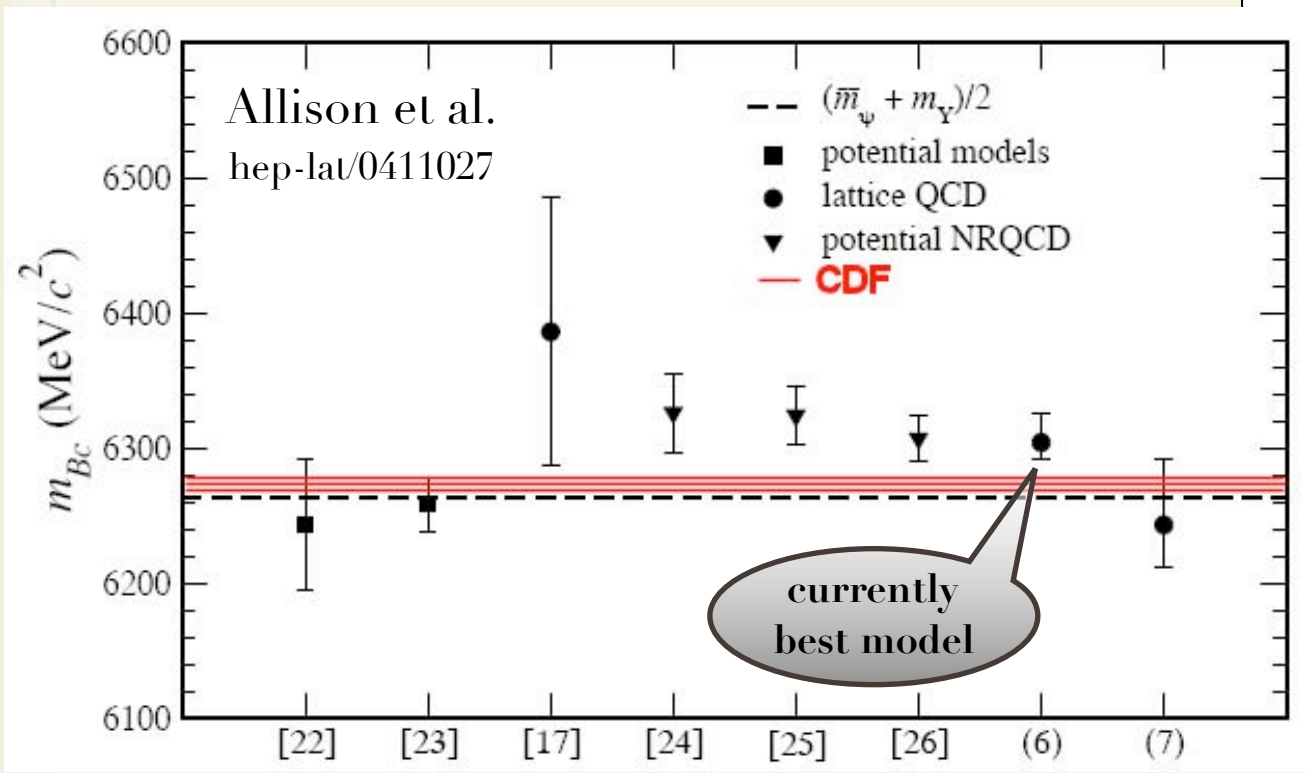


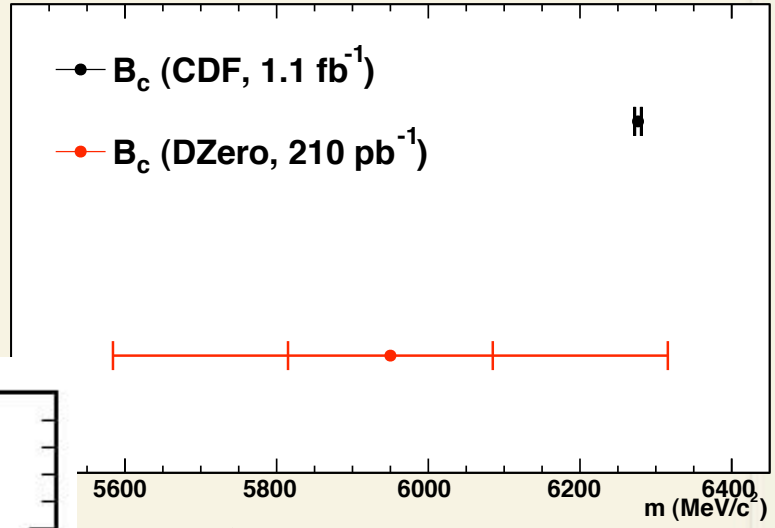
- >6σ significance over search area of 6245-6305 MeV/c^2 using unbinned LH fit

$m(B_c) = 6276.5 \pm 4.0 \pm 2.7$ MeV/c^2

B_c Mass Comparison

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

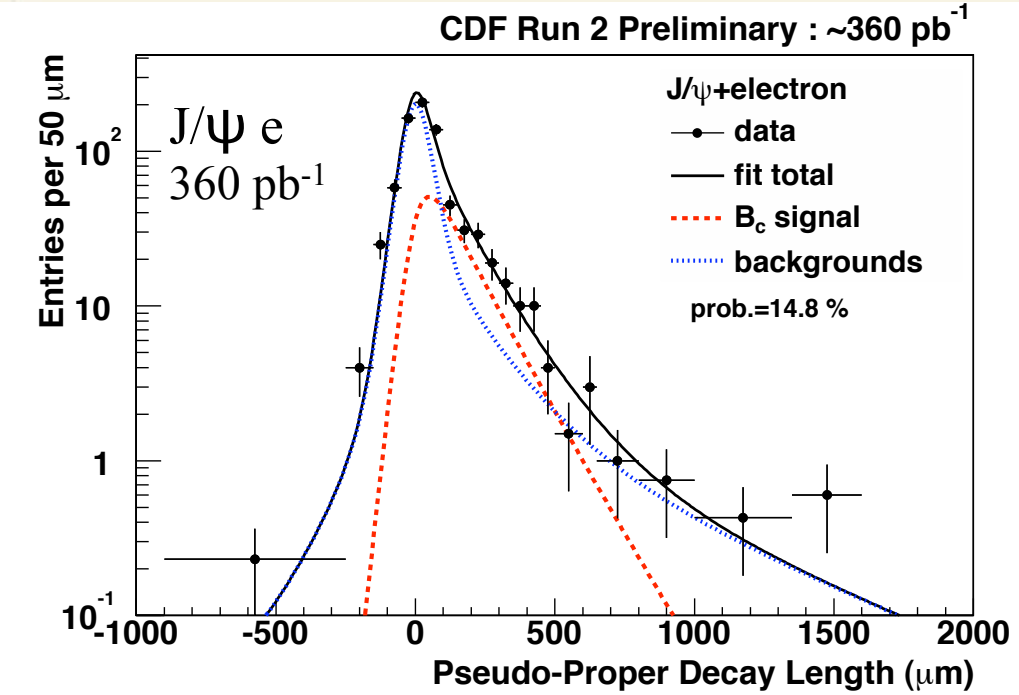


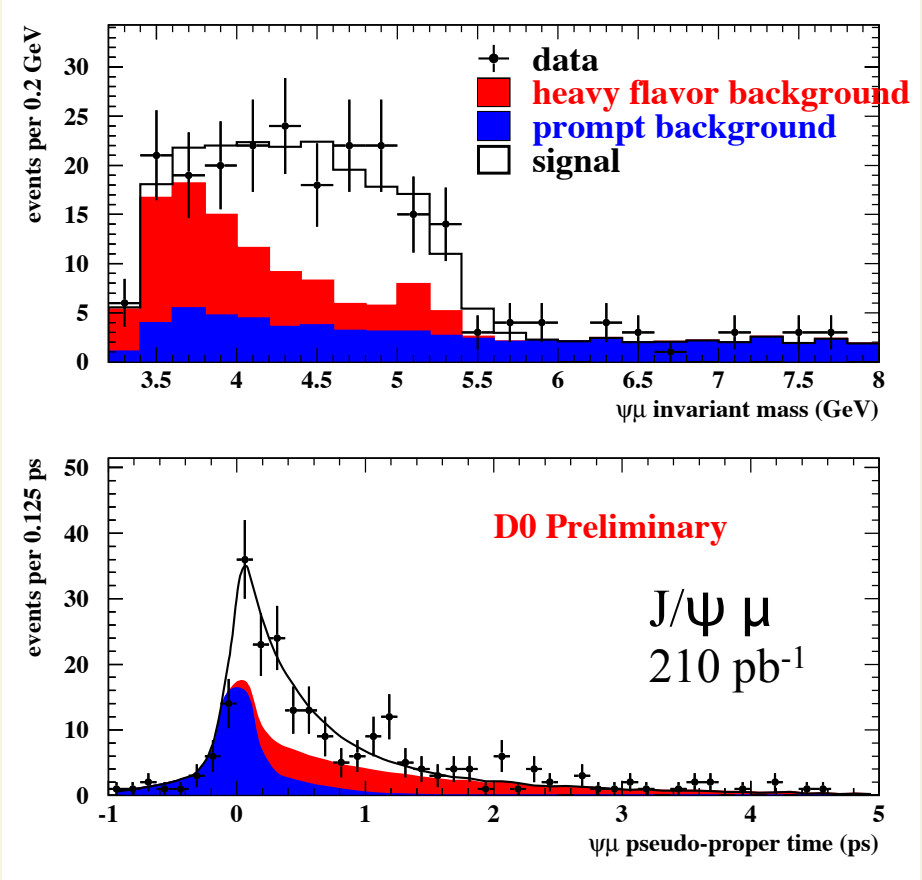


- DØ measurement uses semi-leptonic $B_c \rightarrow J/\psi\ \mu$

[17] H. P. Shanahan, P. Boyle, C. T. H. Davies and H. Newton [UKQCD Collaboration], Phys. Lett. B **453**, 289 (1999).
[21] G. P. Lepage *et al.*, Nucl. Phys. Proc. Suppl. **106**, 12 (2002).
[22] W. k. Kwong and J. L. Rosner, Phys. Rev. D **44**, 212 (1991).
[23] E. J. Eichten and C. Quigg, Phys. Rev. D **49**, 5845 (1994).
[24] N. Brambilla and A. Vairo, Phys. Rev. D **62**, 094019 (2000).
[25] N. Brambilla, Y. Sumino and A. Vairo, Phys. Lett. B **513**, 381 (2001).
[26] N. Brambilla, Y. Sumino and A. Vairo, Phys. Rev. D **65**, 034001 (2002).

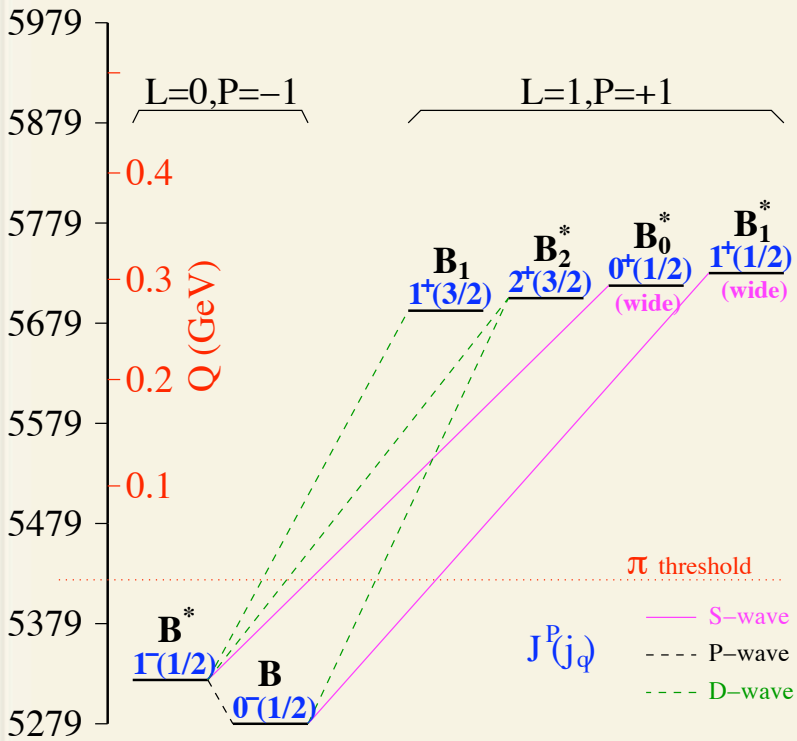
Lifetime: $B_c \rightarrow J/\psi\, \ell\, \nu$





CDF (360 pb^{-1})	$0.474\ ^{+0.073}_{-0.066} \pm 0.033$ ps
DØ (210 pb^{-1})	$0.448^{+0.123}_{-0.096} \pm 0.121$ ps
V.Kiselev hep-py/0308214	0.55 ± 0.15 ps

Excited States: B_d^{**} and B_s^{**}



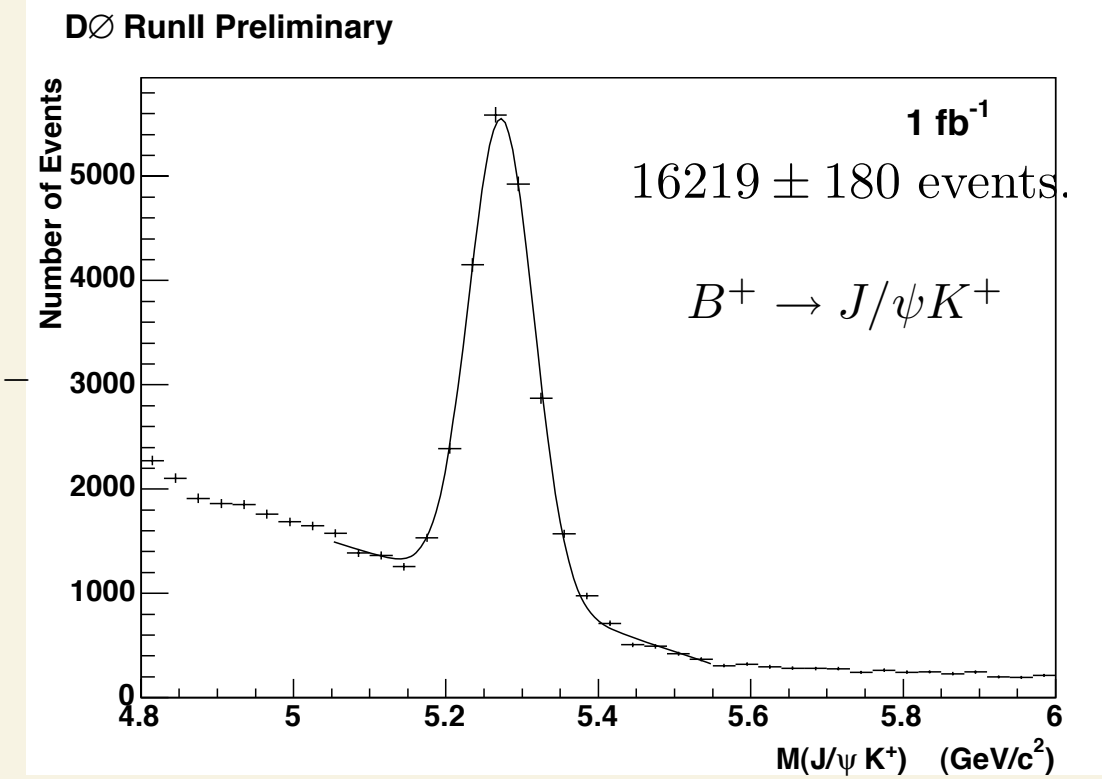
- Spectroscopy of $\bar{b}q$ mesons not well studied
- Only ground state 0^- (B^+, B^0, B_s) and excited 1^- state (B^*) established
- HQET predicts 4 P-wave states for B_d^{**} and B_s^{**}:
  - $B^*_{(s)0}$ and $B^*_{(s)1}$ decay via S-wave => wide states ($\mathcal{O}(100\ \mathrm{MeV}/c^2)$)
  - $B_{(s)1}$ and $B^*_{(s)2}$ decay via D-wave => narrow ($\mathcal{O}(10\ \mathrm{MeV}/c^2)$) states

- Masses, widths and branching ratios predicted with good precision
- Experimental verification can give insight into quark interaction in bound states and aid further development of non-perturbative QCD

B_d** Narrow States

- Decay channels:

$$B_1^0 \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma$$
$$B_2^{*0} \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma$$
$$B_2^{*0} \rightarrow B^+\pi^-$$
$$B^+ \rightarrow J/\psi K^+$$
$$\hookrightarrow \mu^+\mu^-$$



- Photon not reconstructed
- Fit mass difference
  $\Delta M = M(B\pi) - M(B)$
  for all B^+ candidates with
  $5.19 < M(B^+) < 5.36$ (2σ window around B^+ peak)
- Constrain $\Gamma(B_1^0) = \Gamma(B_2^{*0}) = \Gamma$ from theoretical expectations and $M(B^*) - M(B^+) = 45.78\,\mathrm{MeV/c^2}$ using the PDG value

B_d** Narrow States

- Use J/psi and D^0 decay channel:

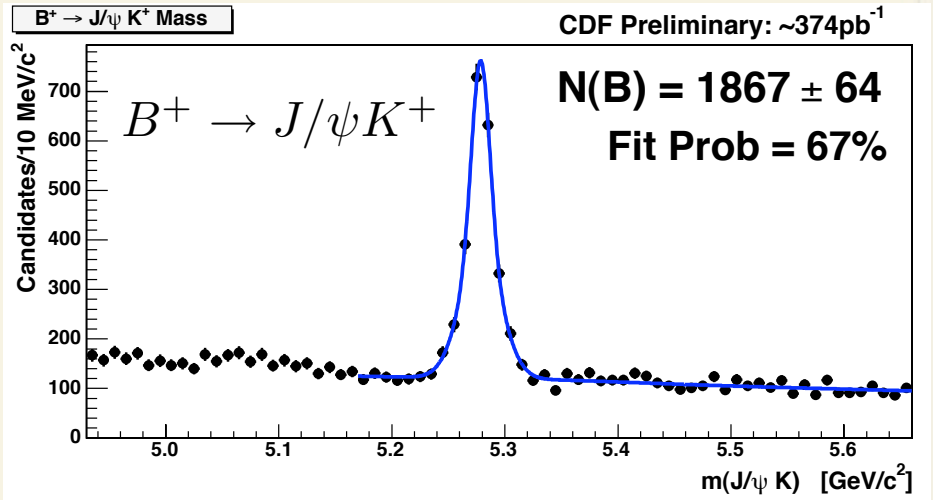
$$B_1^0 \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma$$
$$B_2^{*0} \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma$$
$$B_2^{*0} \rightarrow B^+\pi^-$$
$$B^+ \rightarrow J/\psi K^+ \qquad B^+ \rightarrow \bar{D}^0\pi^+$$
$$\hookrightarrow \mu^+\mu^-$$

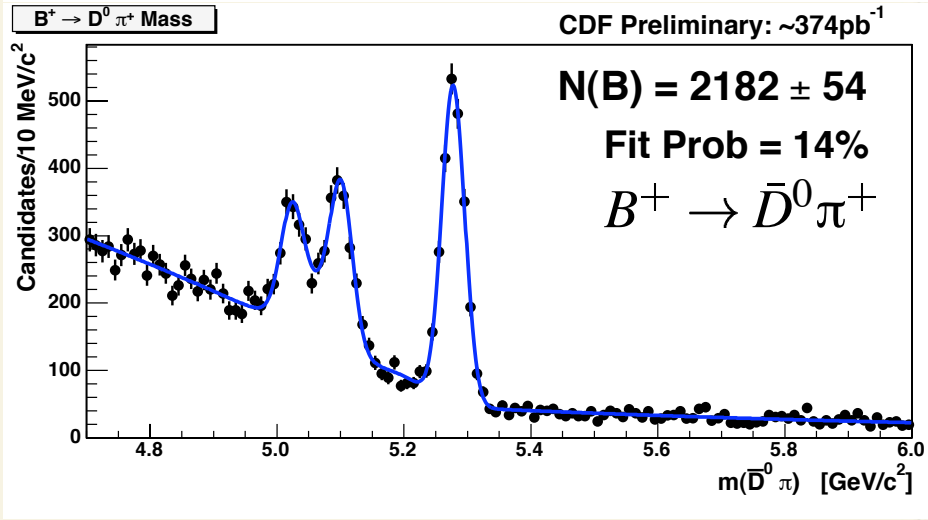
- Fit mass difference

$$\Delta m(B^{**}) = m(B^{**}) - m(B^+) - m(\pi^-).$$

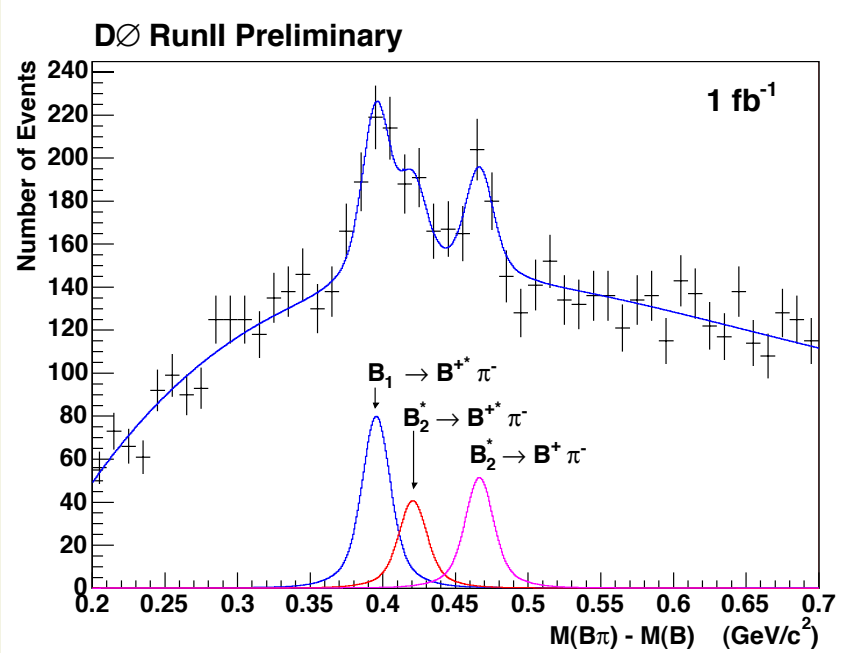
- Fit constrained to theoretical values:

$$M(B^*) - M(B^+) = 45.78\,\mathrm{MeV/c^2}$$
$$\Gamma(B_1^0) = \Gamma(B_2^{*0}) = 16 \pm 6\,\mathrm{MeV/c^2}$$
$$\frac{BR(B_2^* \rightarrow B\pi)}{BR(B_2^* \rightarrow B^*\pi)} = 1.1 \pm 0.3$$

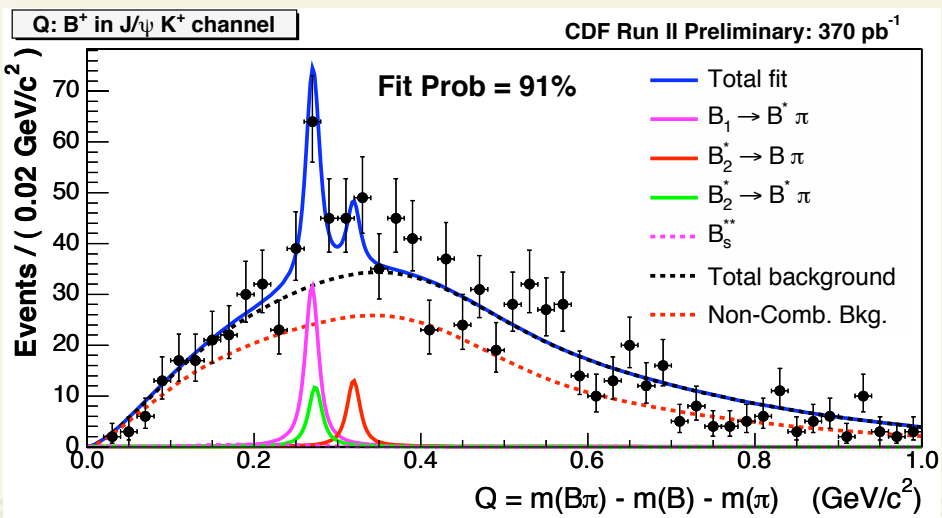


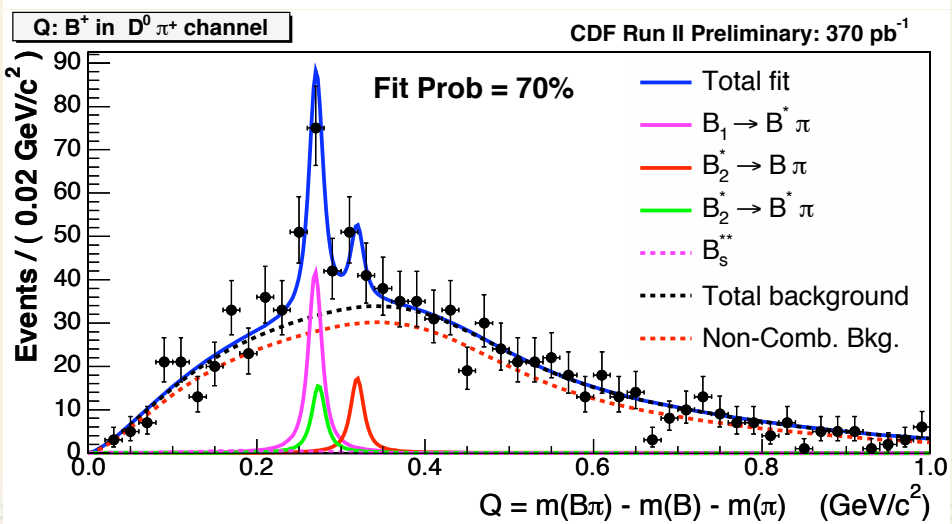


B_1 and B^*_2 observed



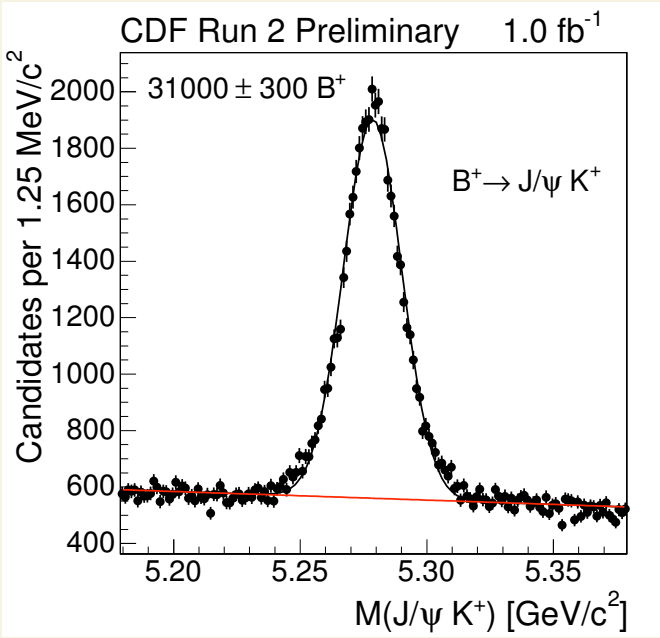
	CDF (370 pb^{-1})	DØ (1fb^{-1})
$m(B_1)$ [MeV/c^2]	5734±3±2	5720.8±2.5±5.3
$m(B^*_2)$ [MeV/c^2]	5738±5±1	5746.0±3.9±5.4
$m(B^*_2) - m(B_1)$ [MeV/c^2]	4±6±2	25.2±3.0±1.1
$\Gamma_1 = \Gamma_2$ [MeV/c^2]	16±6 (fixed)	6.6±5.3±4.2

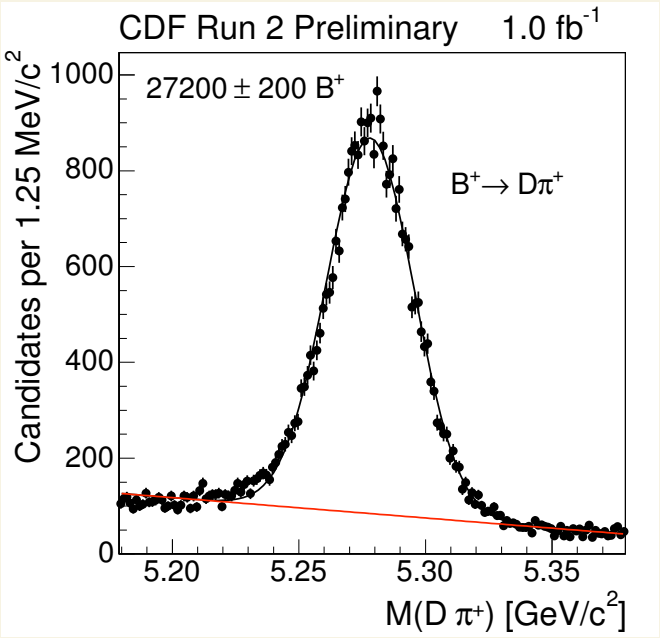




B_s** Narrow States

- Decay to B_s π suppressed by isospin conservation
- $B_s^{**} \to B^+K^- \to [J/\psi K^+]K^-$ ↳ $\mu^+\mu^-$ $\quad B_s^{**} \to B^+K^- \to [\overline{D}^0\pi^+]K^-$ ↳ $K^+\pi^-$



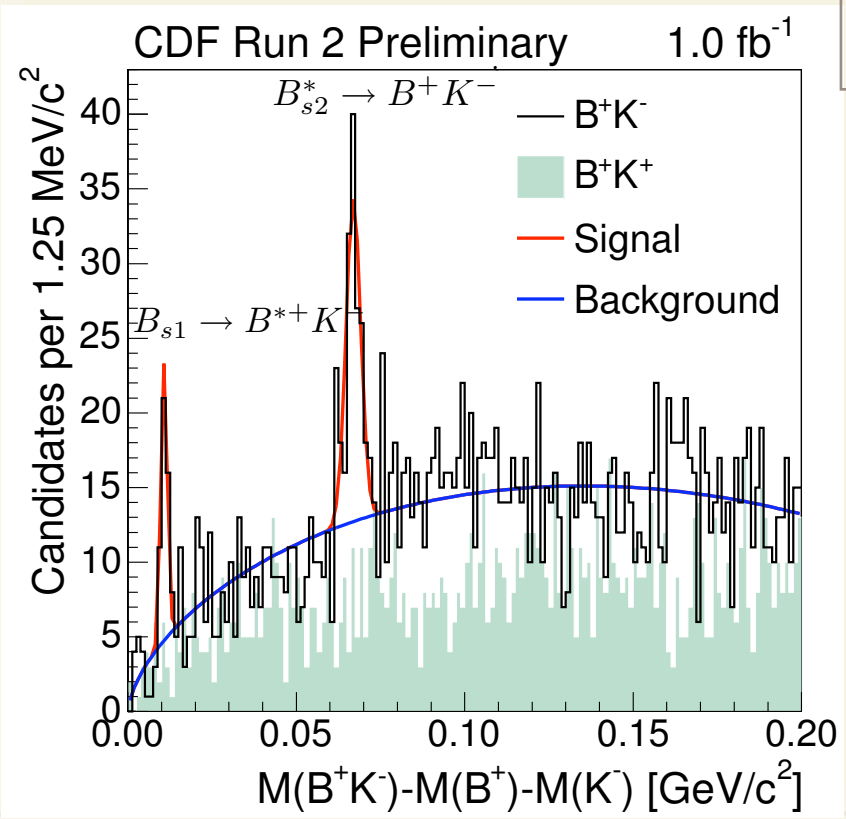


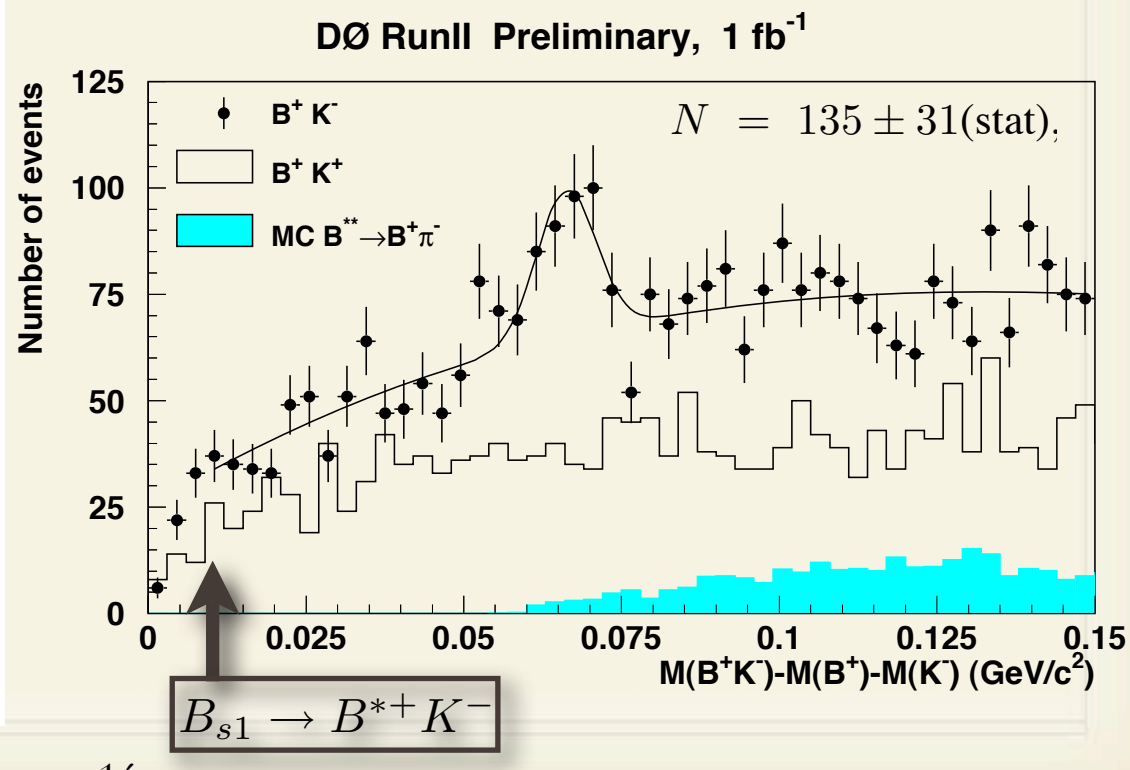
- Final event selection by requiring less than 4 candidates / event and Neural Net cut optimized for best $S/\sqrt{S+B}$

B^*_{s2} observed: B_{s1} too?

- DØ uses same $B \to J/\psi K$ data sample as for B_d^{**} search

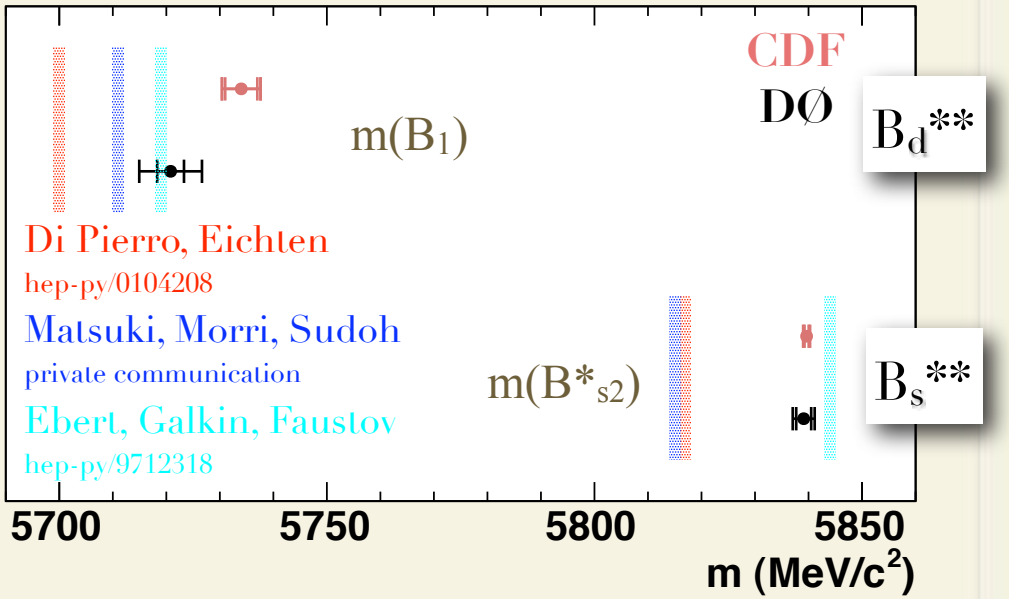
	CDF (1 fb^{-1})	DØ (1 fb^{-1})
$m(B_{s1})$ [MeV/c^2]	5829.4±0.2±0.6	–
$m(B^*_{s2})$ [MeV/c^2]	5839.6±0.4±0.5	5839.1±1.4±1.5
$m(B^*_{s2}) - m(B_{s1})$ [MeV/c^2]	10.20±0.44±0.35	–

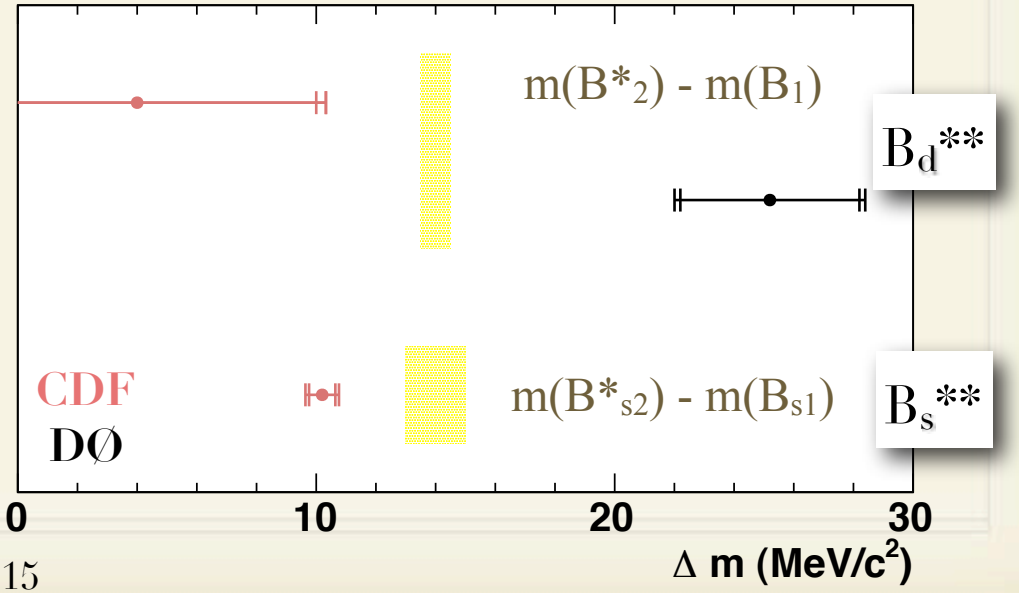




B** Comparison

- Masses of B_1 and B^*_{s2} agree
- Mass differences of CDF are smaller than DØ
- Theories predicts very similar Δm for orbital excitations in $\bar{b}d$ and $\bar{b}s$ system
- Using DØ's Δm as measured in $\bar{b}d$, B_{s1} mass would be ~5814 MeV/c^2
- Mass is too low for decay into $B^{*+}K^-$
  - Possible explanation for missing 2nd peak in DØ
- But what does CDF see if not B_{s1}?



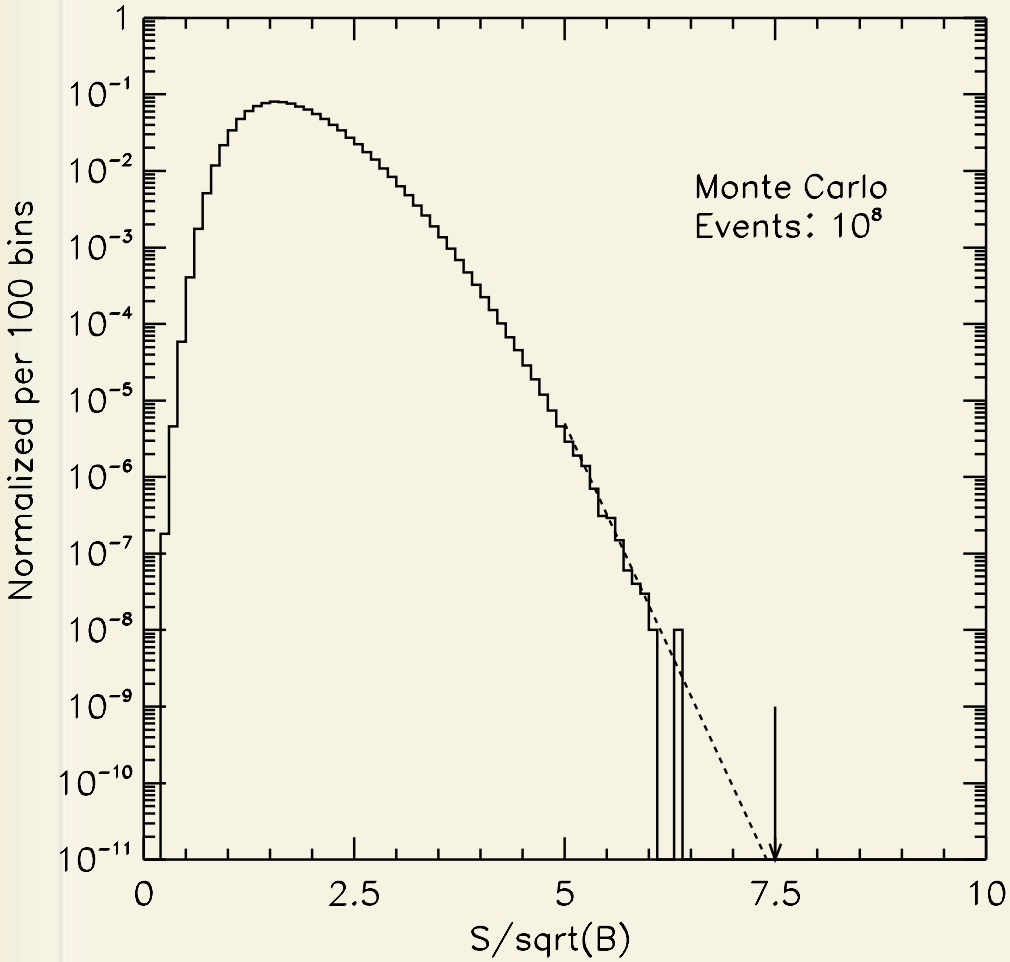


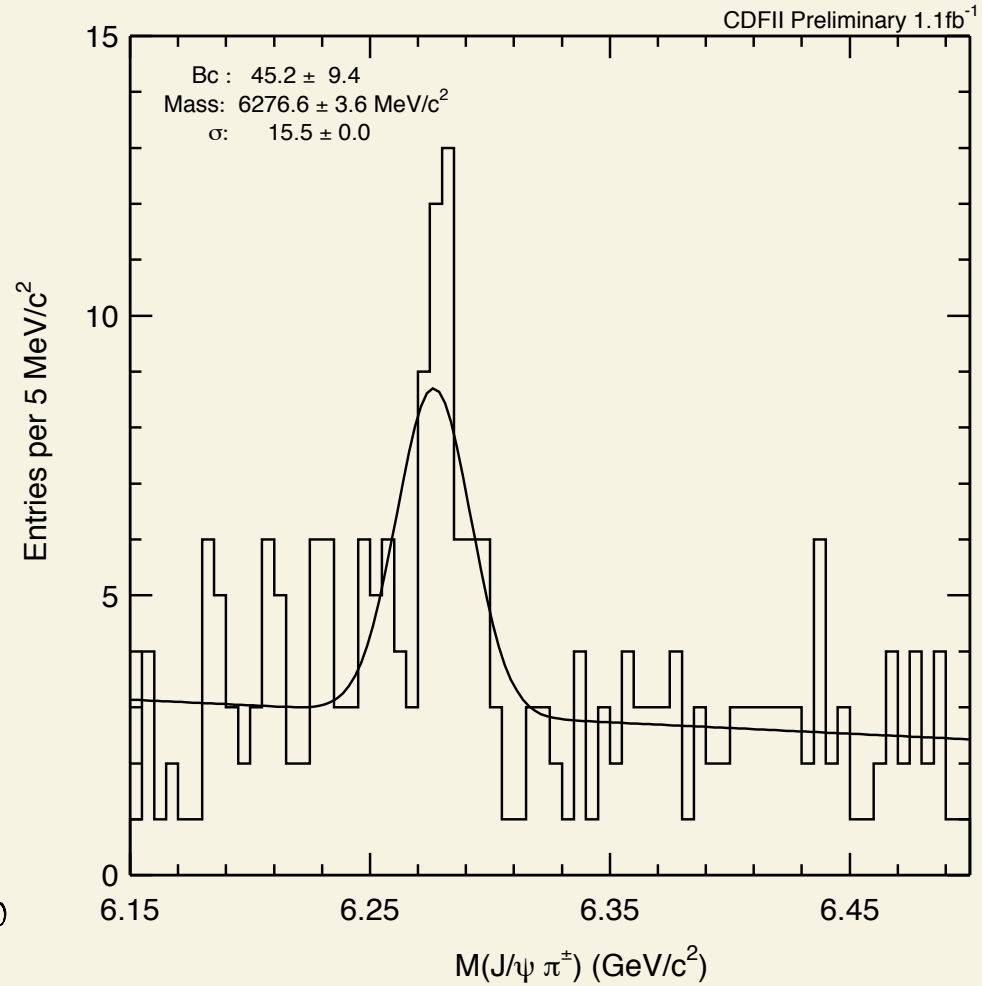
Summary

- New precise mass measurement of $m(B_c) = 6276.5 \pm 4.0 \pm 2.7$ MeV/c^2
- B_c lifetime measured by both CDF and DØ in agreement with theory
- 2 narrow states of B_d^{**} system measured & consistent with theory predictions
- Puzzle of B_s^{**} excited states
  - CDF measures both narrow states with $\Delta m \approx 10$ MeV/c^2
  - DØ only sees B^*_{s2}
  - Using DØ measurement of Δm from B_d^{**}, no B_{s1} peak expected
  - Improved measurement of Δm in B_d^{**} system could shed light on discrepancy in B_s^{**} system

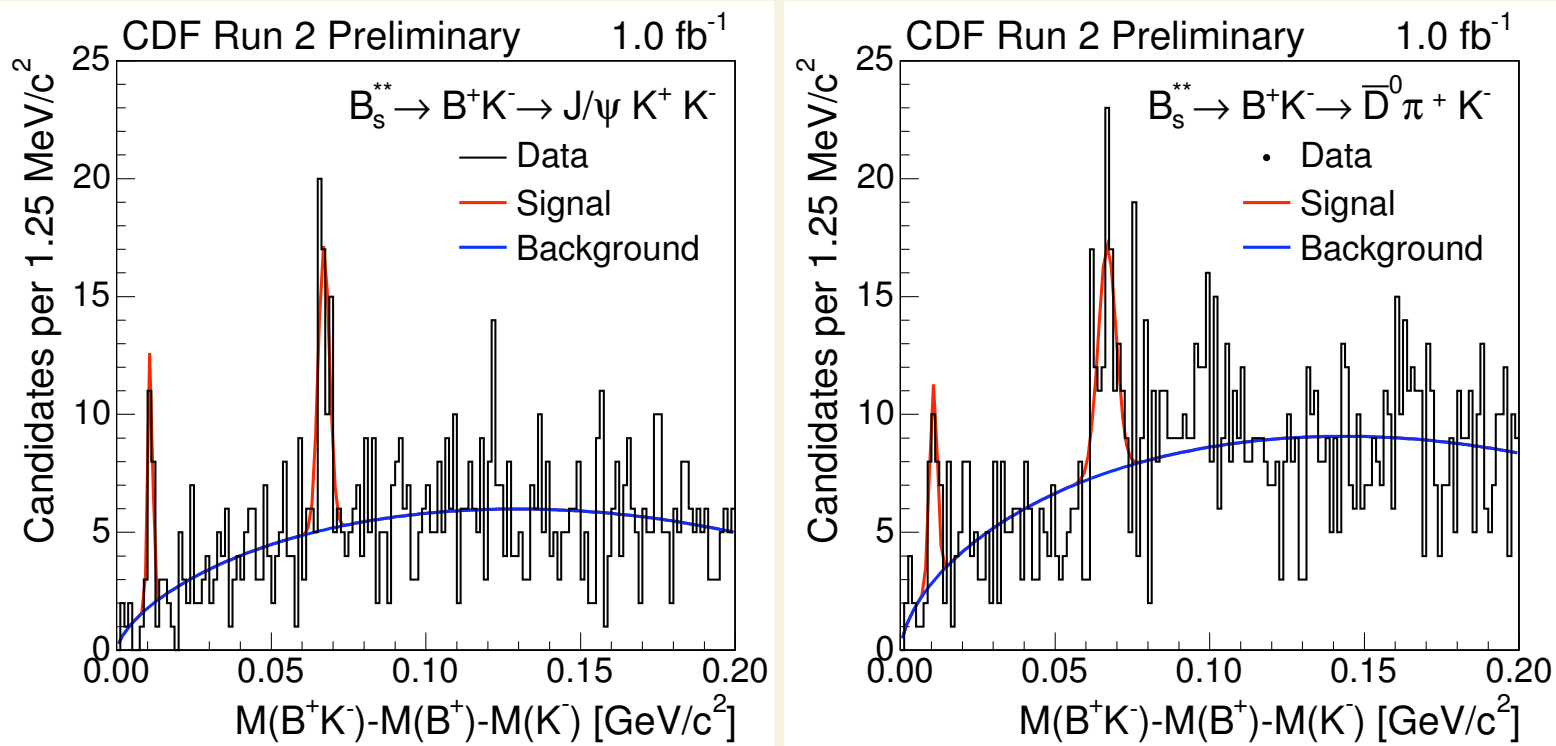
Backup Slides

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



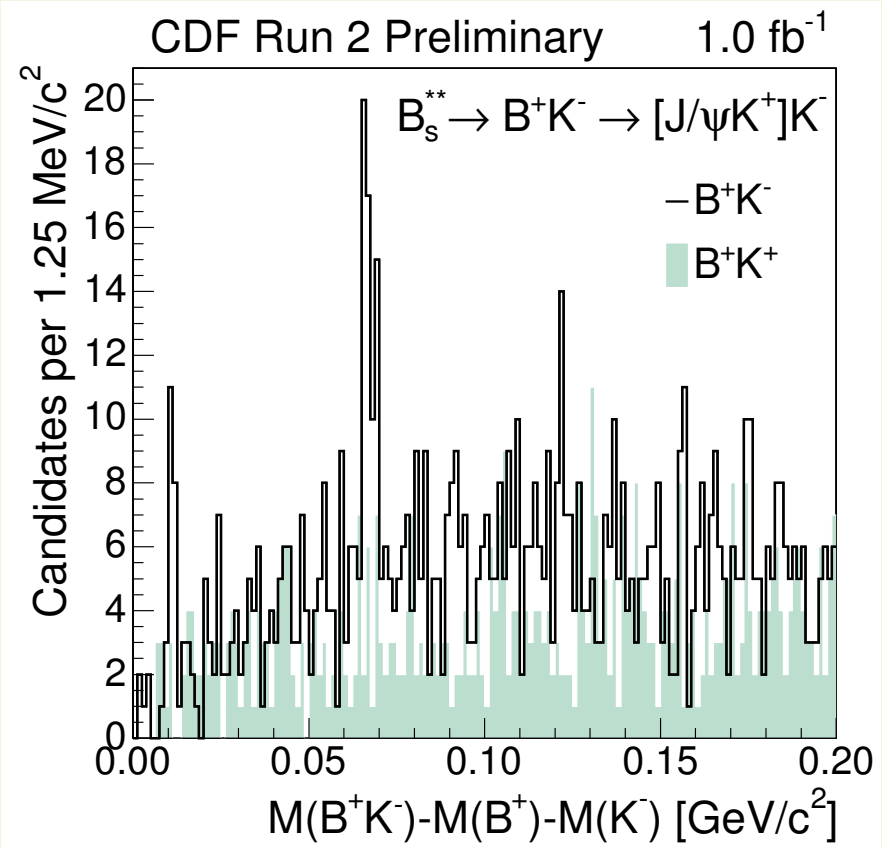


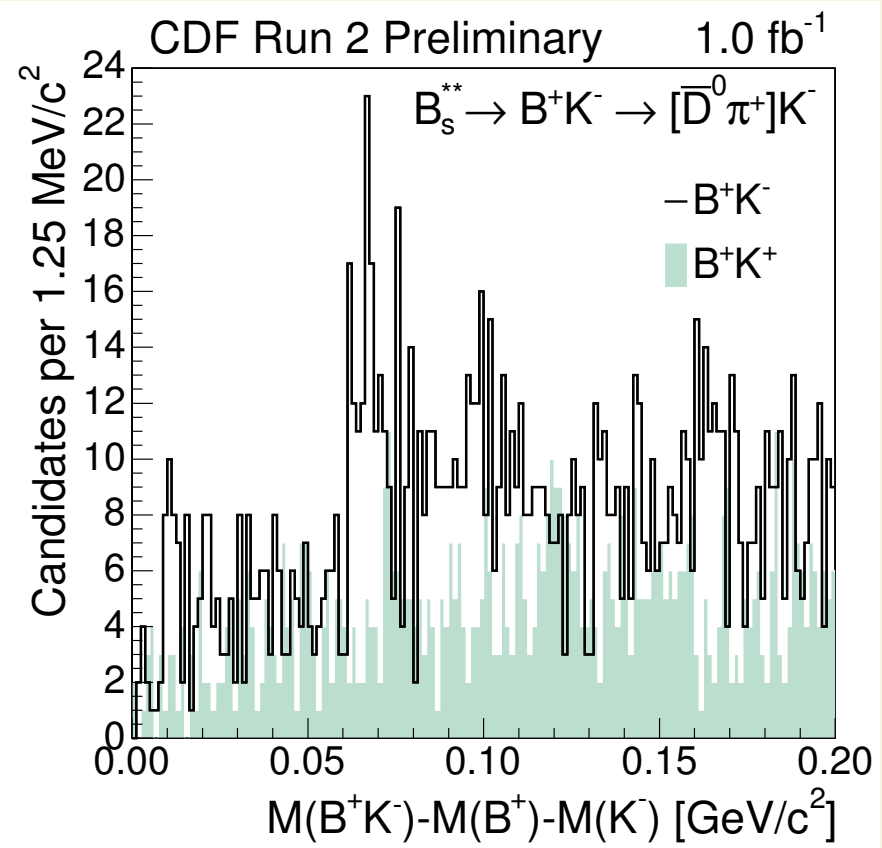
B_s^{**}



	B_{s1}		B_{s2}^*	
	$B^+ \to J/\psi K^+$	$B^+ \to \overline{D}^0\pi^+$	$B^+ \to J/\psi K^+$	$B^+ \to \overline{D}^0\pi^+$
Q [MeV/c^2]	10.87 ± 0.19	10.68 ± 0.46	67.03 ± 0.44	66.85 ± 0.76
σ [MeV/c^2]	0.64 ± 0.25	1.18 ± 0.56	1.79 ± 0.42	2.88 ± 0.75
N	16.98 ± 5.14	20.66 ± 7.12	44.15 ± 13.36	55.74 ± 19.20

B_s^{**}


CDF Run 2 Preliminary
1.0 fb-1
B**s → B+K- → [J/ψK+]K-
−B+K-
B+K+
Candidates per 1.25 MeV/c2
M(B+K-)-M(B+)-M(K-) [GeV/c2]


CDF Run 2 Preliminary
1.0 fb-1
B**s → B+K- → [D̄0π+]K-
−B+K-
B+K+
Candidates per 1.25 MeV/c2
M(B+K-)-M(B+)-M(K-) [GeV/c2]

Mystery of X(3872)

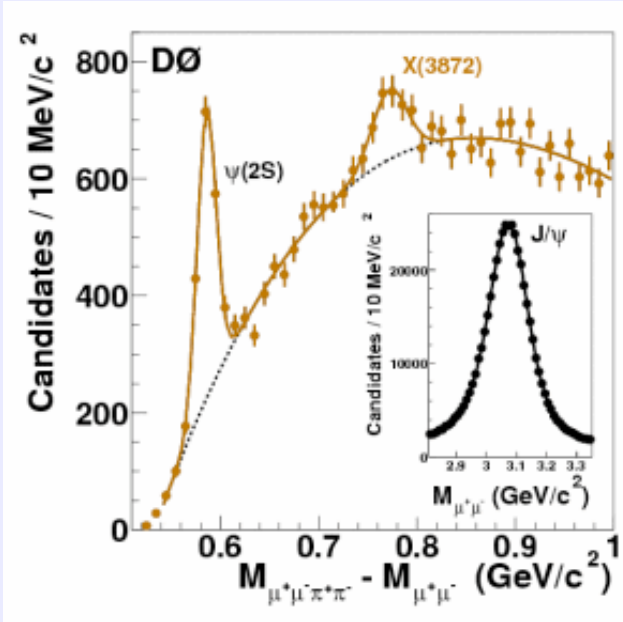
Aug'03: Belle announces discovery of $X(3872) \to J/\psi \pi^+ \pi^-$

What is it? Pros/cons for any explanation

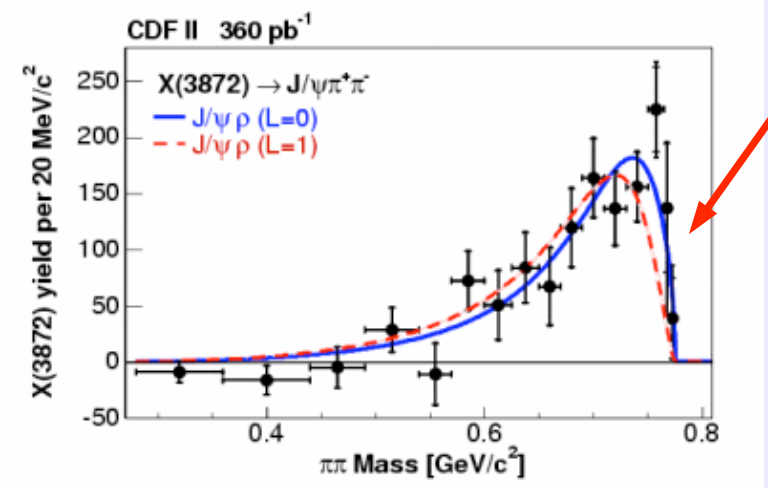
- DD* molecule?
- Excited ccbar state

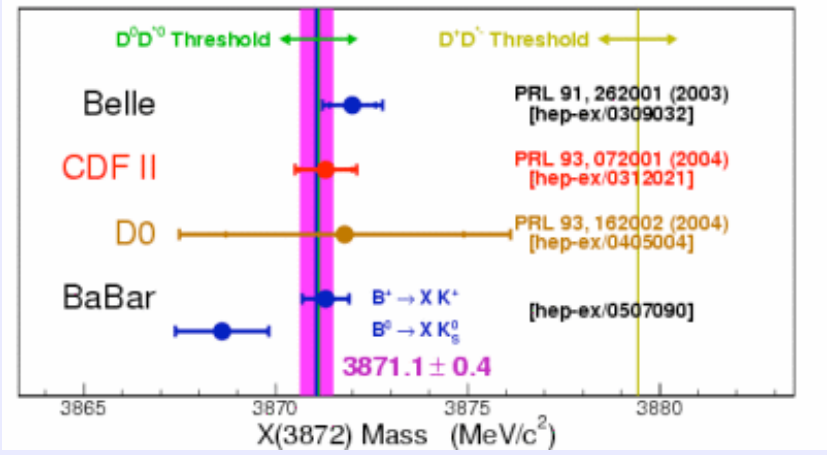
Results from CDF and D0 rapidly follow

- observation and mass at ppbar
- production properties, prompt fraction
  ➔ consistent with 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





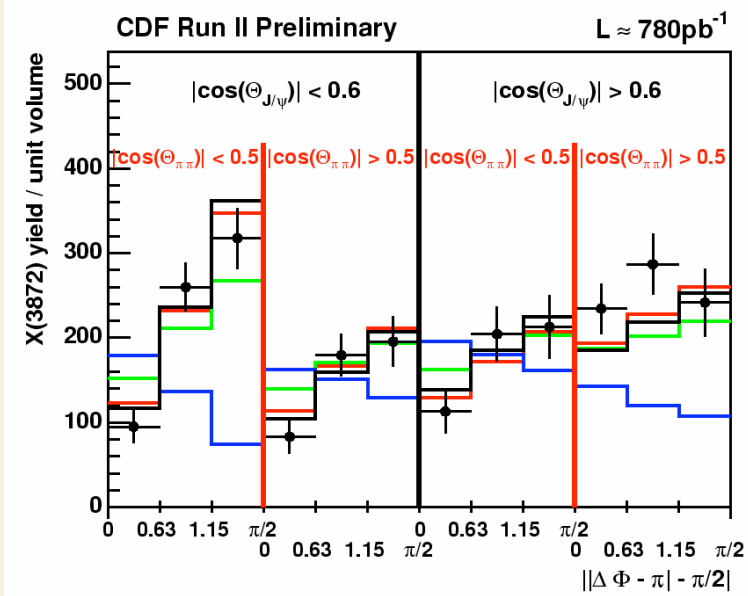
X(3872): Results for J^{PC}

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	$4.1\cdot10^{-6}$
0^{-+}	103.6	$3.5\cdot10^{-17}$
0^{+-}	129.2	$\leq1\cdot10^{-20}$
0^{++}	163.1	$\leq1\cdot10^{-20}$



X(3872) data points

Fit model

3 best:

- 1^{++}_{p}
- 2^{-+}_{p}
- 1^{--}_{s}

the worst

- 0^{++}_{p}

Result:

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

Cross-check on Ψ(2S):

- same final state, J^{PC} reproduce

1