Spectroscopy of B-like Hadrons at the Tevatron

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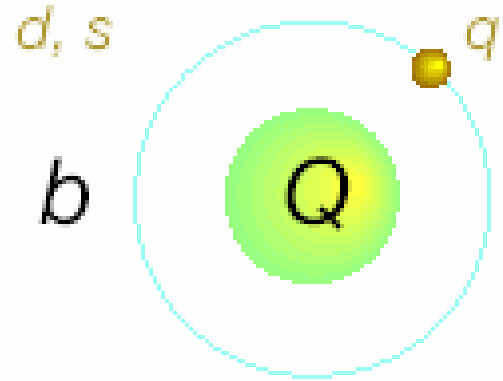
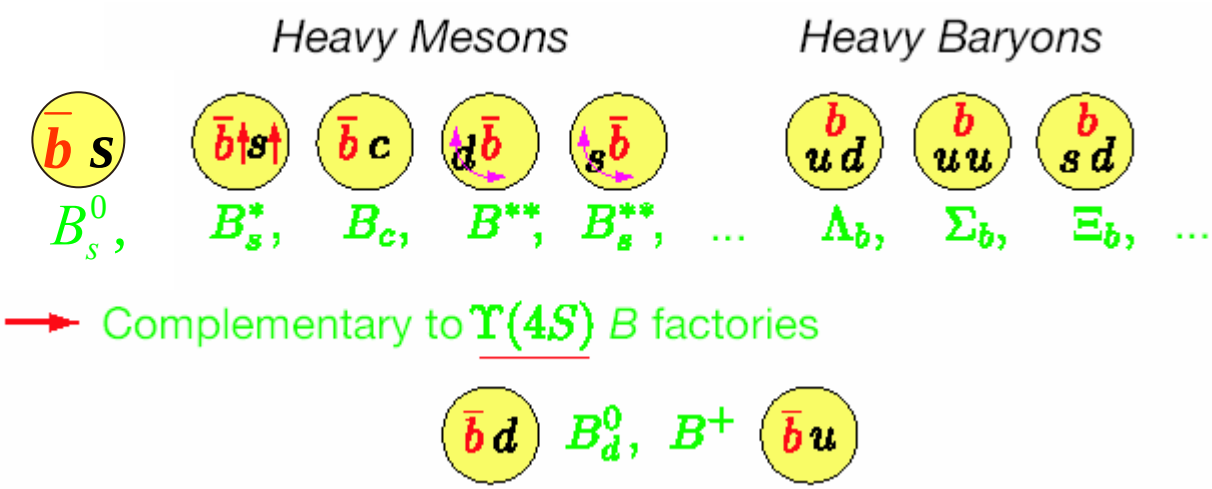
Why B Spectroscopy?

- Heavy bound-state mesons and baryons are the "hydrogen atoms" of the quark world
- B spectroscopy measurements provide sensitive tests of potential models, heavy quark effective theory (HQET), and lattice gauge theory





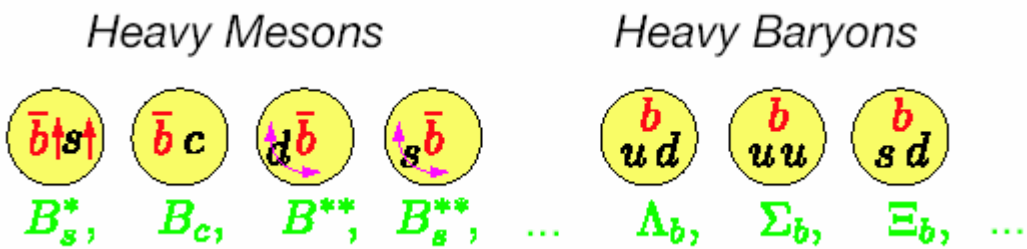
Why B Spectroscopy at the Tevatron?

- b-quark production cross-section is large

$$\sigma(e^+e^- \to B\overline{B}) \approx 1\,nb \quad \text{at } \Upsilon(4S)$$

$$\sigma(p\overline{p} \to b\overline{b}) \approx 5\,\mu b \quad \text{at 2 TeV}$$

- Tevatron energy sufficient to create states not accessible at the e^+e^- B factories



B Fragmentation Fractions

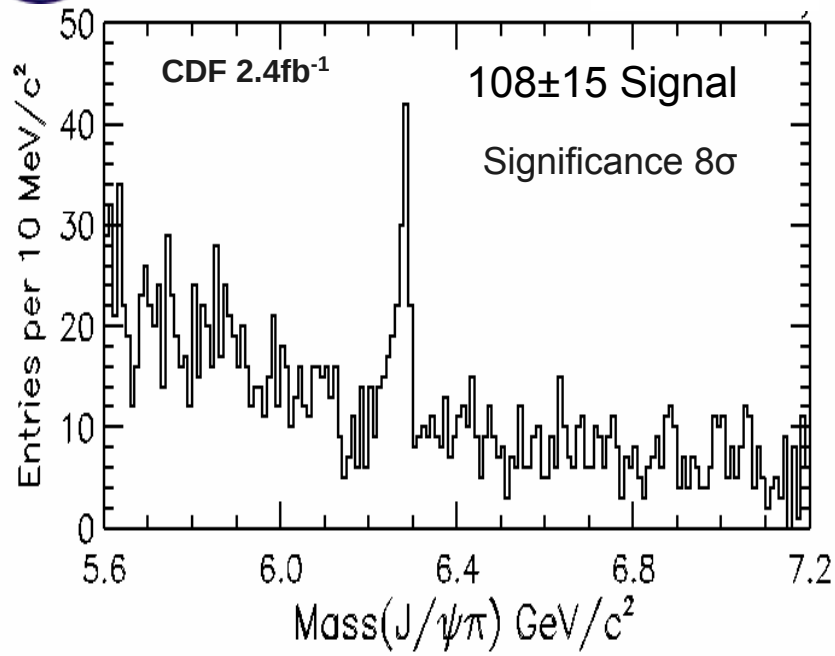
- B^+ ($\bar{b}u$) (39.8±1.0)%
- B^0 ($\bar{b}d$) (39.8±1.0)%
- B^0_s ($\bar{b}s$) (10.4±1.4)%
- b baryons (bud) (9.9±1.7)%

B_c ($\bar{b}c$) Meson

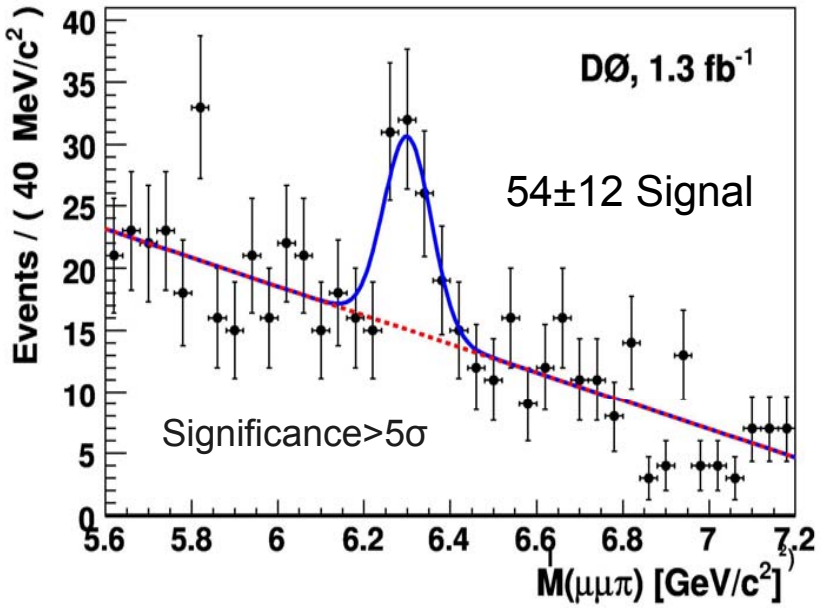
- Bound state of two different heavy quarks
- Precise mass measurements from CDF and DØ using fully reconstructed $B_c \rightarrow J/\psi\pi^+$ decays
  - test predictions of heavy-quark bound-state models

B_c Mass

PRL 100, 182002 (2008)



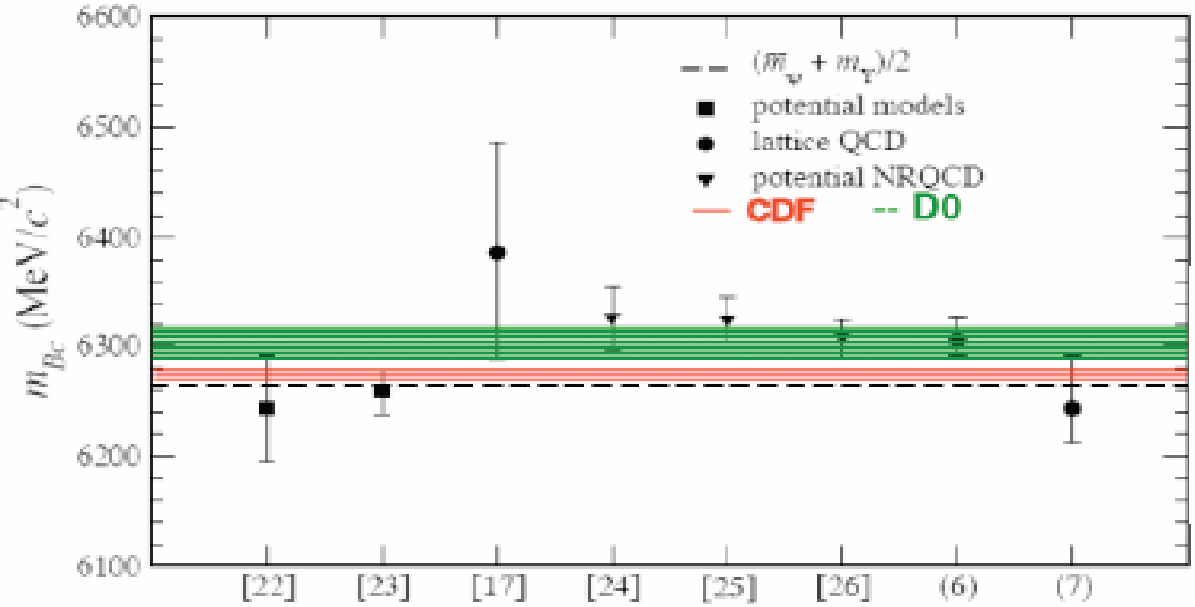
PRL 101, 012001 (2008)



M = 6275.6 ± 2.9 ± 2.5 MeV/c^2

M = 6300 ± 14 ± 5 MeV/c^2

B_c Mass



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[7] HPQCD, Fermilab Lattice, and UKQCD Collaborations, I. F. Allison *et al.*, Nucl. Phys. B, Proc. Suppl. **140**, 440 (2005).

[17] UKQCD Collaboration, H. P. Shanahan, P. Boyle, C. T. H. Davies, and H. Newton, Phys. Lett. B **453**, 289 (1999).

[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).

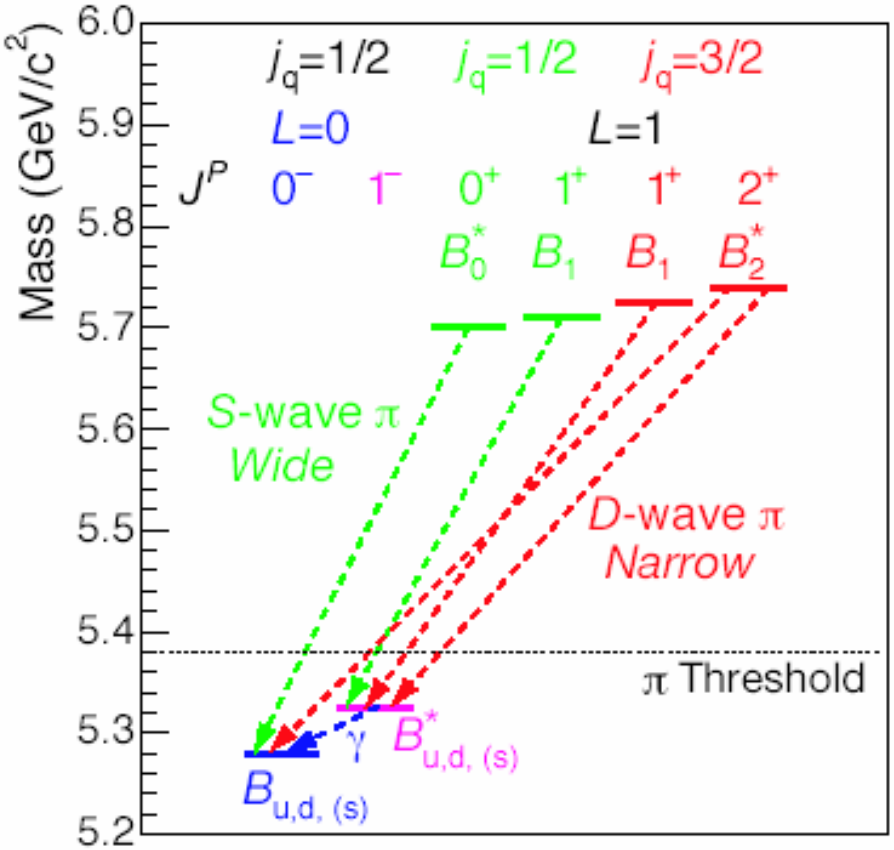
[25] N. Brambilla, Y. Sumino, and A. Vairo, Phys. Lett. B **513**, 381 (2001).

[26] N. Brambilla, Y. Sumino, and A. Vairo, Phys. Rev. D **65**, 034001 (2002).

- Theory:
  - $M = 6304 \pm 12^{+18}_{-0}$ MeV/c^2 (lattice QCD) [Phys. Rev. Lett. 94, 172001 (2005)]
  - $M = 6247\text{-}6286$ MeV/c^2 (non-rel. potential models) [Phys. Rev. D 70, 054017 (2004)]

Orbitally Excited B^{**} Mesons

- Several quark models yield mass, width and branching fraction predictions
- Experimental observations can help to elucidate quark interactions inside bound states
- Improve development of non-perturbative QCD



- B^*_0,B^*_1 widths ~100s MeV; too broad to be distinguished from background
- B_1, B^*_2 widths ~10 MeV

Orbitally Excited B^{**} Meson Masses

45.8 MeV γ
not observed

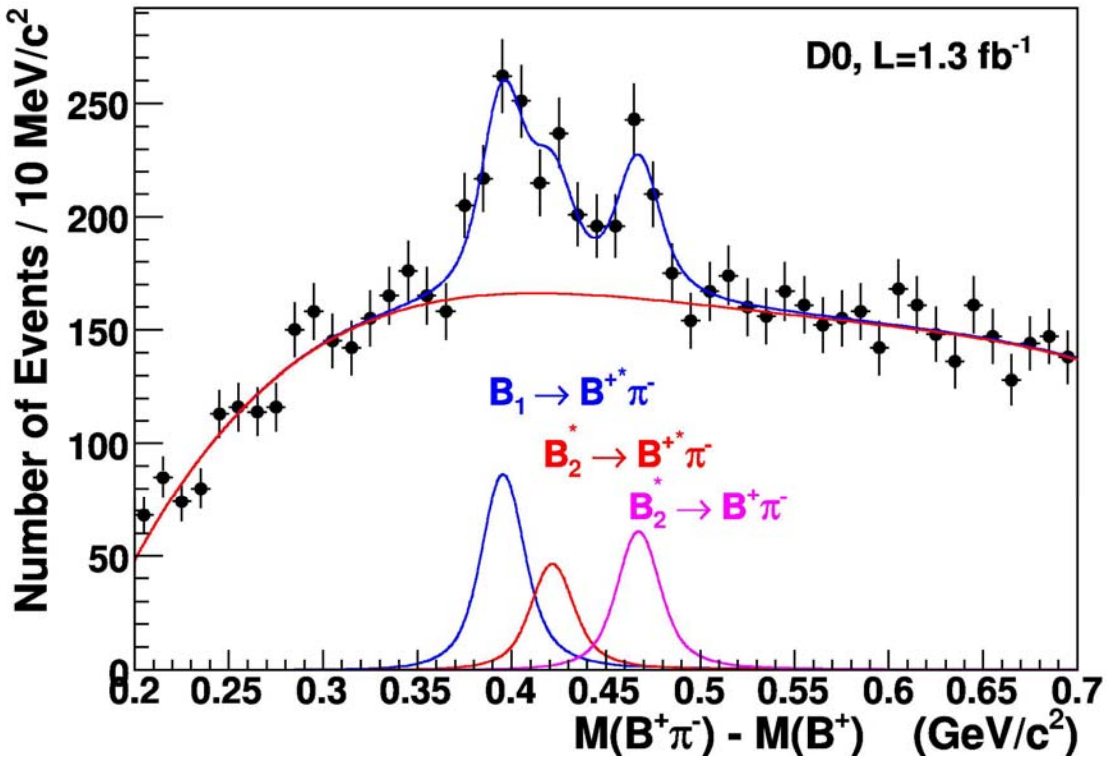
$$B_1, B_2^* \to B^{(*)+}\pi^-$$

$$B^{*+} \to B^+\gamma, B^+ \to J/\psi K^+$$

$$J/\psi \to \mu^+\mu^-$$

- N=662±91
- Significance>7σ

PRL **99**,172001 (2007)



$M(B_1) = 5720.6 \pm 2.4 \pm 1.4$ MeV/c^2

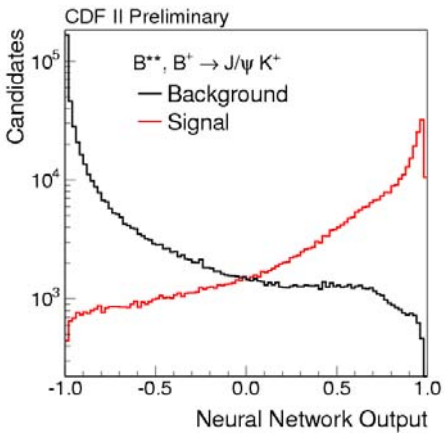
$M(B^*_2) = 5746.8 \pm 2.4 \pm 1.7$ MeV/c^2

Orbitally Excited B^{**} Meson Masses

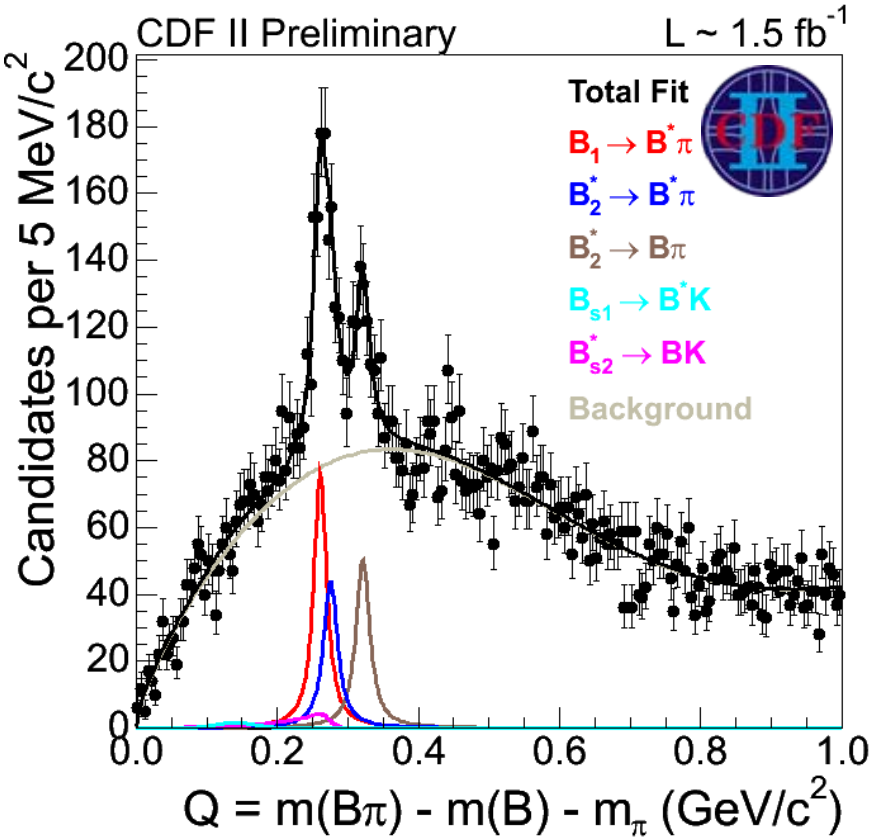
$$B_1, B_2^* \to B^{(*)+}\pi^-$$

$$B^{*+} \to B^+\gamma$$

$$B^+ \to J/\psi K^+ / \overline{D}^0 \pi^+ (\pi^+\pi^-)$$



- Use Neural Net for preselection
- N=1306±154

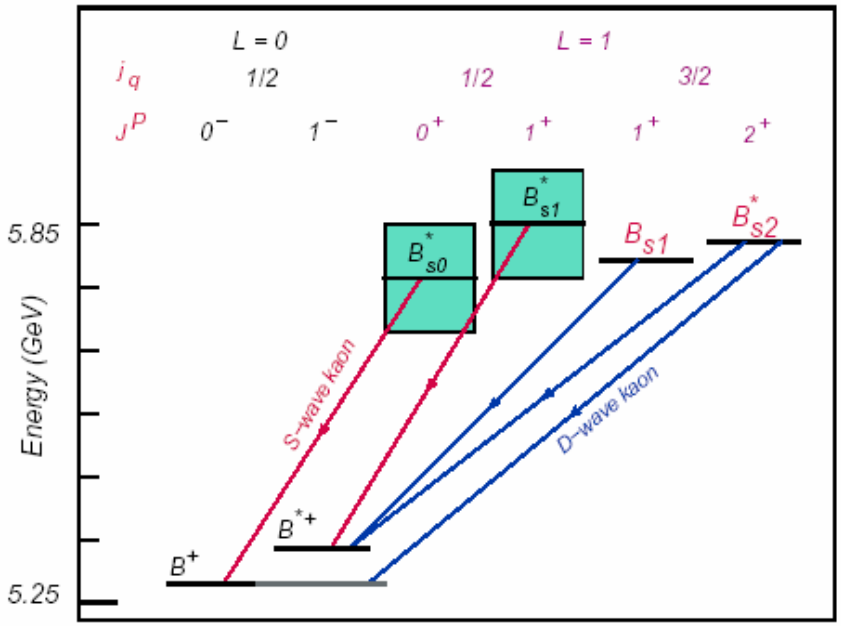


$$M(B_1) = 5725.3^{+1.6}_{-2.1}(\text{stat})^{+0.8}_{-1.1}(\text{syst})\,\text{MeV/c}^2$$

$$M(B_2^*) = 5739.9^{+1.7}_{-1.8}(\text{stat})^{+0.5}_{-2.6}(\text{syst})\,\text{MeV/c}^2$$

$$\Gamma(B_2^*) = 22.1^{+3.6}_{-3.1}(\text{stat})^{+3.5}_{-2.6}(\text{syst})\,\text{MeV/c}^2$$

Orbitally Excited B_s^{**} Meson



$$B_{s1}, B^*_{s2} \to B^{(*)+} K^-$$

$$B^{*+} \to B^+ \gamma$$

$$B^+ \to J/\psi K^+$$ CDF/D∅

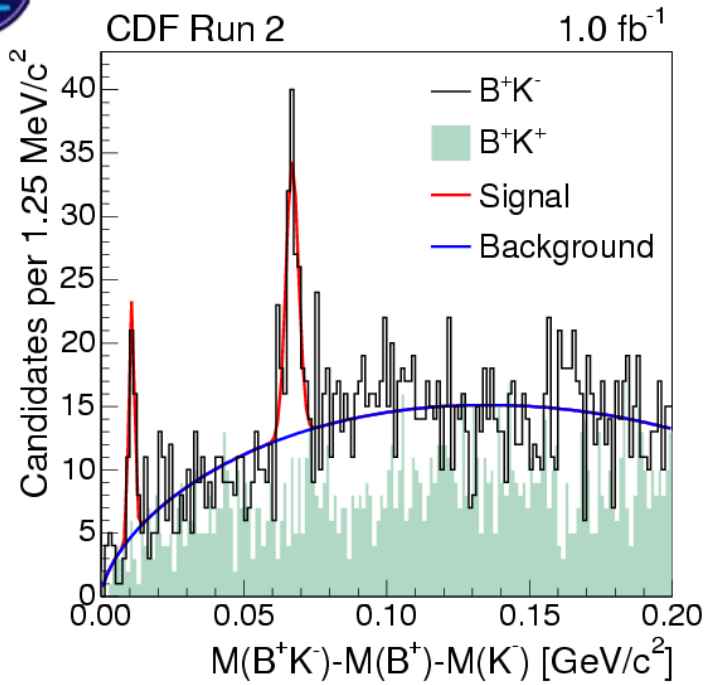
$$B^+ \to \overline{D}^0 \pi^+$$ CDF

- Theory:
  - $M(B_{s1})$: 5805 – 5891 MeV/c^2
  - $M(B^*_{s2})$: 5820 - 5903 MeV/c^2
  - Natural width ~1MeV/c^2, depending on mass

E. J. Eichten, C. T. Hill, and C. Quigg, Phys. Rev. Lett. **71**, 4116 (1993); D. Ebert, V. O. Galkin, and R. N. Faustov, Phys. Rev. D **57**, 5663 (1998); S. Godfrey and R. Kokoski, *ibid.* **43**, 1679 (1991); A. F. Falk and T. Mehen, *ibid.* **53**, 231 (1996); M. Di Pierro and E. Eichten, *ibid.* **64**, 114004 (2001); A. M. Green *et al.*, *ibid.* **69**, 094505 (2004); W. A. Bardeen, E. J. Eichten, and C. T. Hill, *ibid.* **68**, 054024 (2003); P. Colangelo, F. De Fazio, and R. Ferrandes, Nucl. Phys. B, Proc. Suppl. **163**, 177 (2007).

B^{**} Meson Mass

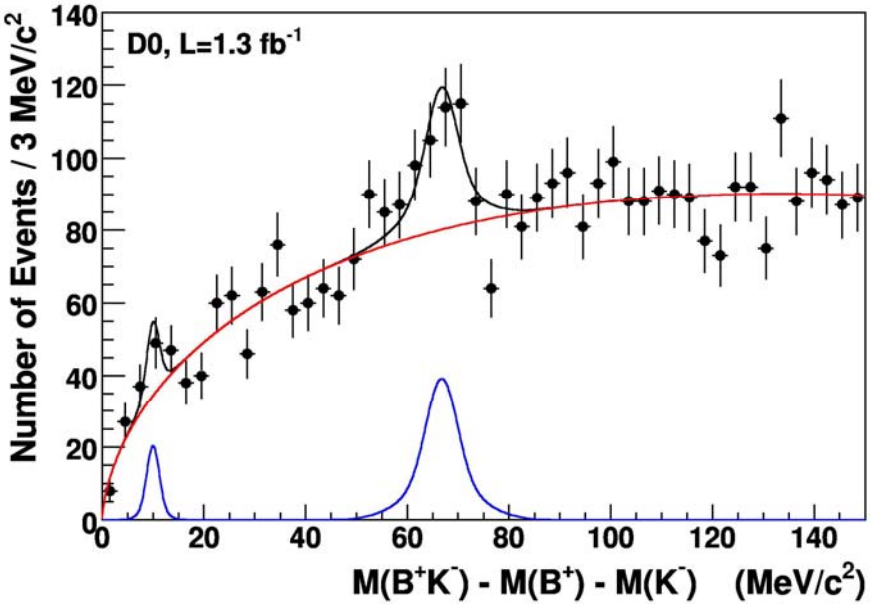
PRL **100**,082001 (2008)



N=36±9 (B_{s1}), N=93±23 (B^*_{s2})
Significance>5σ

$M(B_{s1}) = 5829.4 \pm 0.7$ MeV/c^2
$M(B^*_{s2}) = 5839.6 \pm 0.7$ MeV/c^2

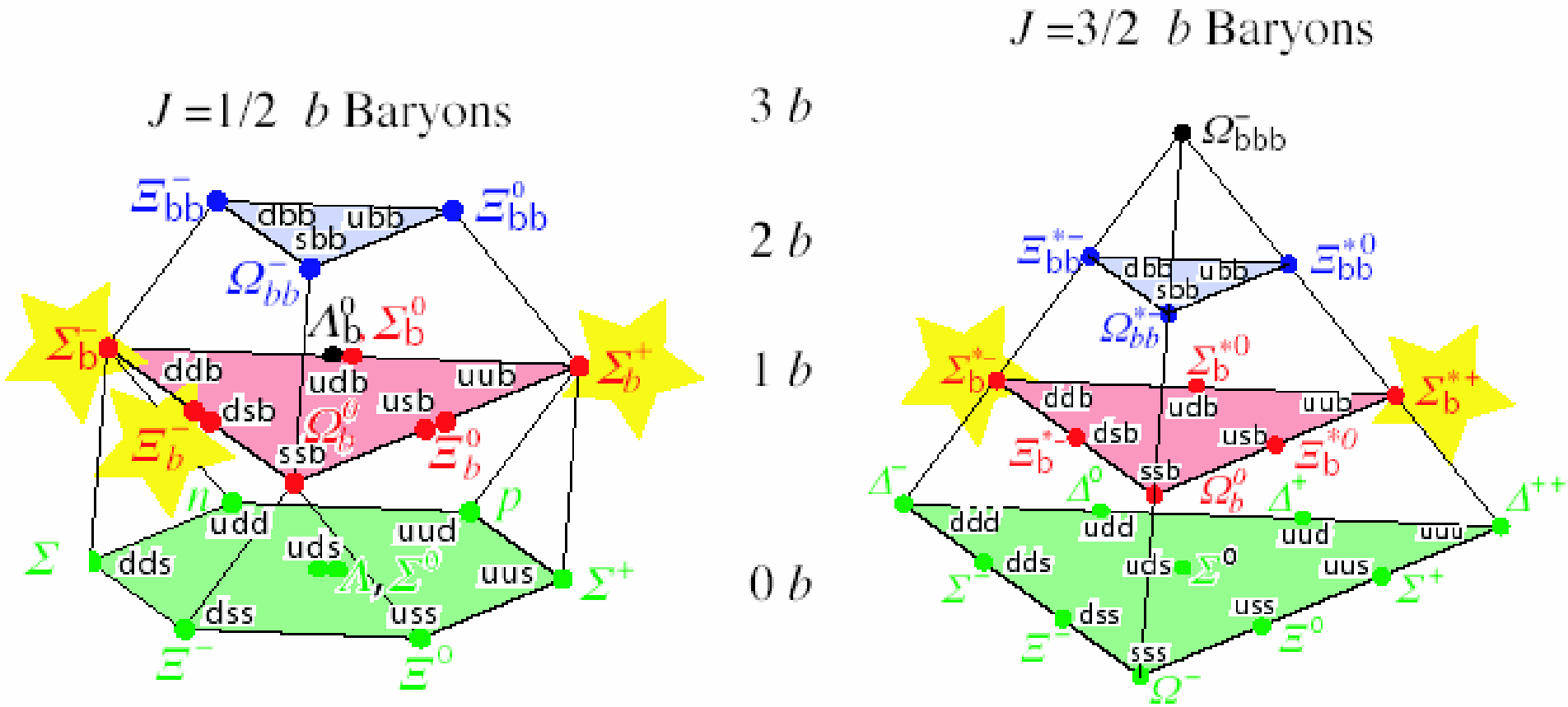
PRL **100**,082002 (2008)



N=25±10 (B_{s1}), N=125±25 (B^*_{s2})
Significance>5σ (B^*_{s2})

$M(B^*_{s2}) = 5839.6 \pm 1.1 \pm 0.7$ MeV/c^2

b Baryons



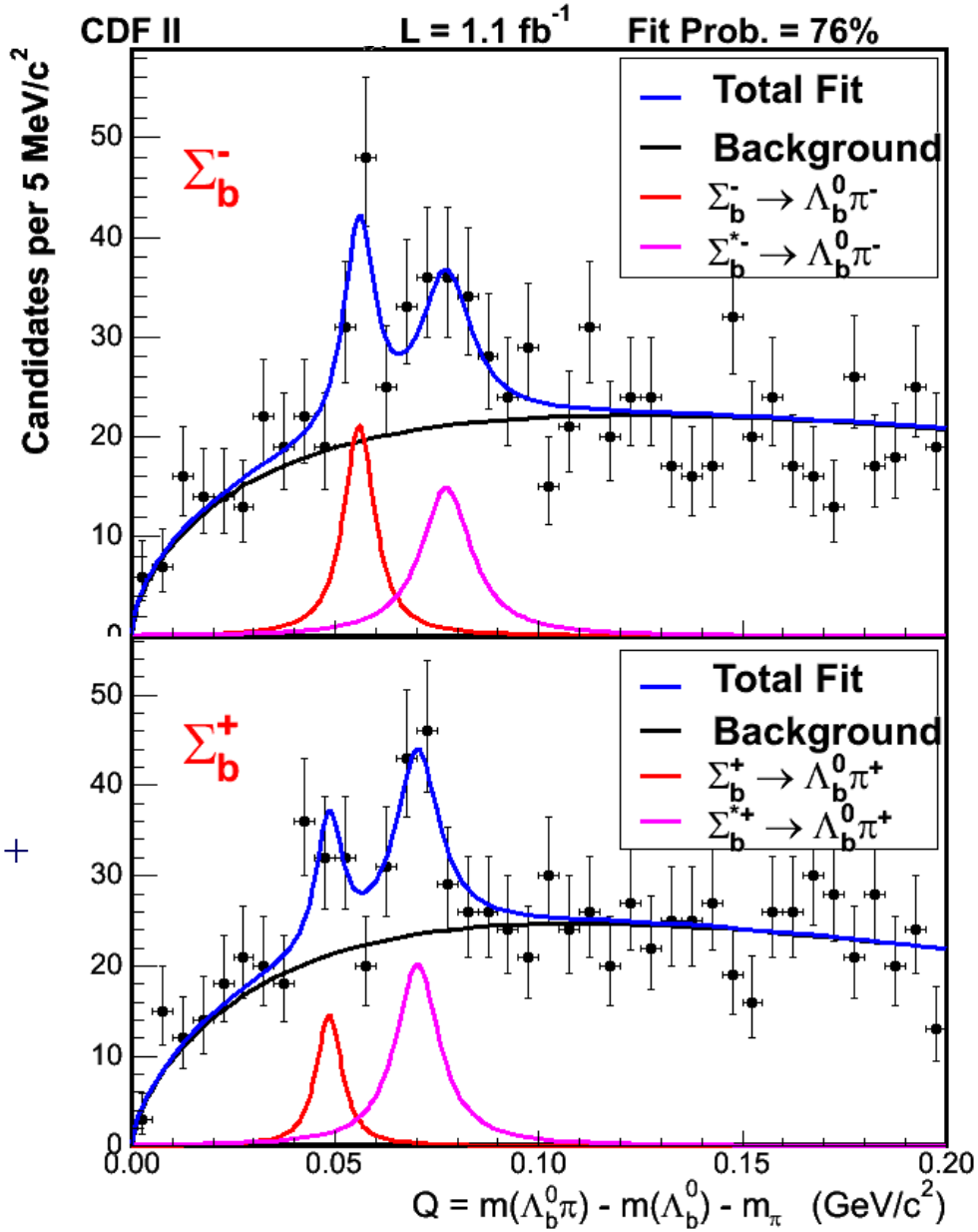
- Quark model successfully predicts observed B meson spectrum
- Until recently, Λ_b^0 (udb) was the only observed b baryon

$\Sigma_b^{+(*)}$ (uub) and $\Sigma_b^{-(*)}$ (ddb) Discovery

- Uses fully reconstructed decays collected by a two-track trigger

$$\Sigma_b^{(*)\pm} \to \pi^{\pm}\Lambda_b$$
$$\to \pi^{-}\Lambda_c^{+}$$
$$\to pK^{-}\pi^{+}$$

PRL 99, 202001 (2007)



$\Sigma_b^{+(*)}$ and $\Sigma_b^{-(*)}$ Masses

State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

$M(\Lambda_b^0) = 5619.7 \pm 1.2 \pm 1.2$ MeV/c^2

PRL 96, 202001 (2006)

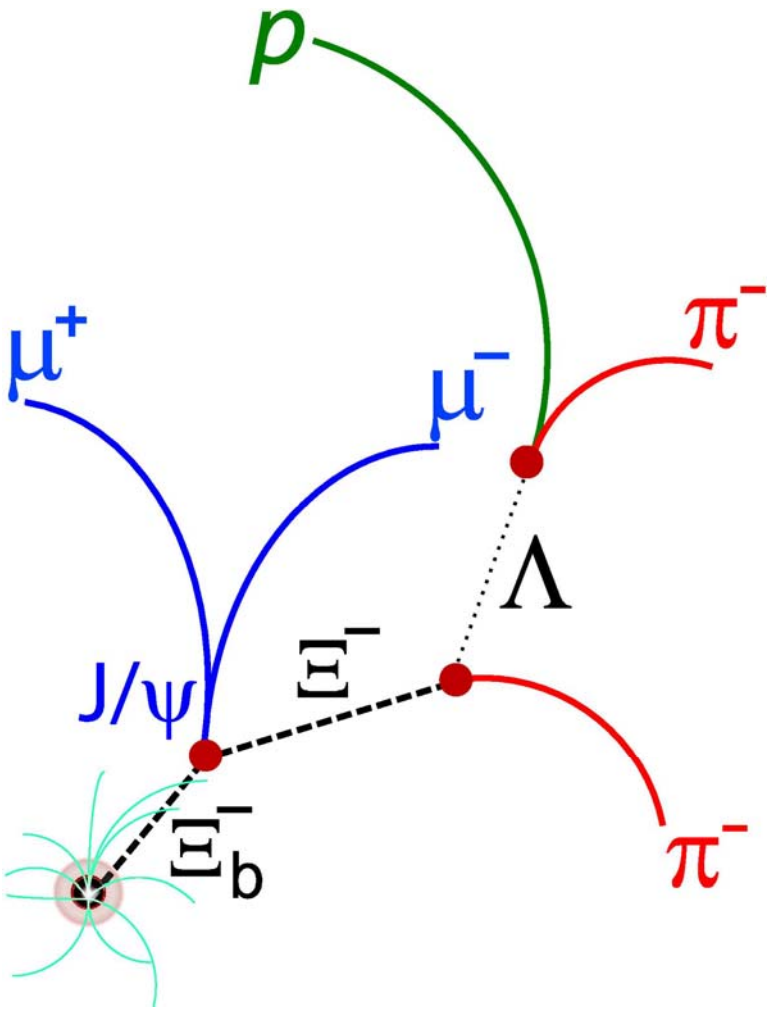
- Theory:

Σ_b property	Expected value (MeV/c^2)
$m(\Sigma_b) - m(\Lambda_b^0)$	180 - 210
$m(\Sigma_b^*) - m(\Sigma_b)$	10 - 40
$m(\Sigma_b^-) - m(\Sigma_b^+)$	5 - 7
$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim$8, $\sim$15

D. P. Stanley and D. Robson, Phys. Rev. Lett. **45**, 235 (1980). D. P. Stanley and D. Robson, Phys. Rev. D **21**, 3180 (1980). D. Izatt, C. DeTar, and M. Stephenson, Nucl. Phys. **B199**, 269 (1982). J. M. Richard and P. Taxil, Phys. Lett. B **128**, 453 (1983). J. L. Basdevant and S. Boukraa, Z. Phys. C **30**, 103 (1986). W. Y. P. Hwang and D. B. Lichtenberg, Phys. Rev. D **35**, 3526 (1987). A. Martin and J. M. Richard, Phys. Lett. B **185**, 426 (1987). D. B. Lichtenberg, R. Roncaglia, J. G. Wills, and E. Predazzi, Z. Phys. C **47**, 83 (1990).
E. Jenkins, Phys. Rev. D **54**, 4515 (1996). E. Jenkins, Phys. Rev. D **55**, R10 (1997).
C. Albertus, J. E. Amaro, E. Hernandez, and J. Nieves, Nucl. Phys. **A740**, 333 (2004). D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D **72**, 034026 (2005). S. Capstick, Phys. Rev. D **36**, 2800 (1987).
R. Roncaglia, D. B. Lichtenberg, and E. Predazzi, Phys. Rev. D **52**, 1722 (1995). M. Karliner and H. J. Lipkin, hep-ph/0307243; condensed version in Phys. Lett. B **575**, 249 (2003).
K. C. Bowler *et al.* (UKQCD Collaboration), Phys. Rev. D **54**, 3619 (1996). N. Mathur, R. Lewis, and R. M. Woloshyn, Phys. Rev. D **66**, 014502 (2002).
J. L. Rosner, Phys. Rev. D **57**, 4310 (1998). J. L. Rosner, Phys. Rev. D **75**, 013009 (2007).
J. G. Körner, M. Krämer, and D. Pirjol, Prog. Part. Nucl. Phys. **33**, 787 (1994).

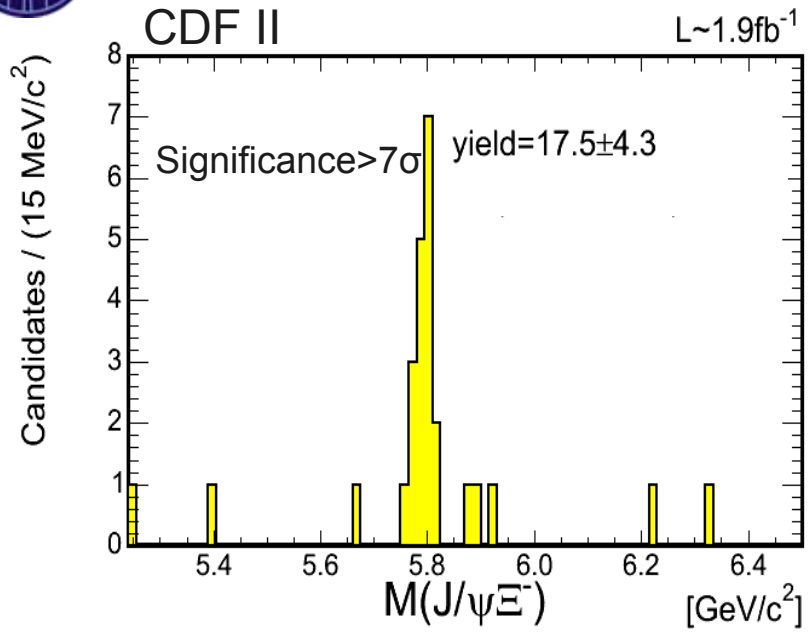
Ξ_b (dsb) Discovery

- "Triple-Scoop" baryon comprising valence quarks from all three known generations [dsb]
- Theory: $5.7 < M < 5.8$ GeV/c^2
  - HQET [Phys. Rev. D51, 1125 (1995); 55, E5853 (1997)]
  - NRQCD [Phys. Rev. D55, R10 (1997); 54, 4515 (1996)]
  - Lattice NRQCD [Phys. Rev. D66, 014502 (2002)]

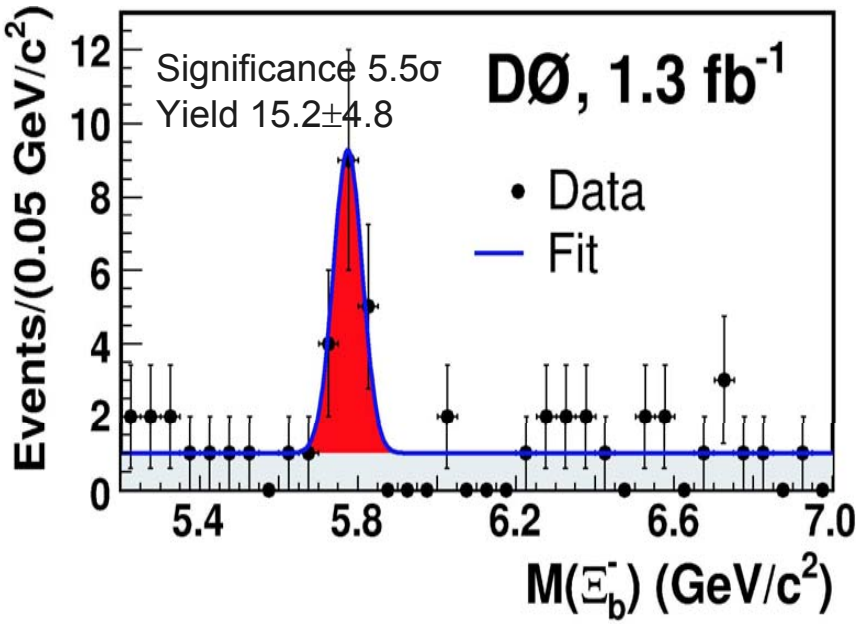


Ξ_b Mass

PRL 99, 052002 (2007)



PRL 99, 052001 (2007)



M = 5792.9 ± 2.4 ± 1.7 MeV/c^2

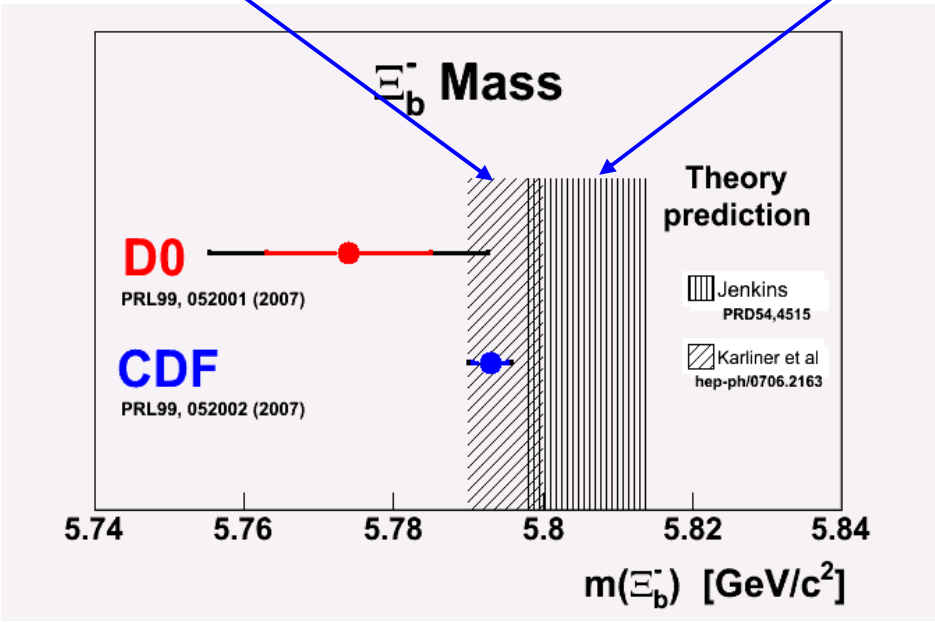
M = 5774 ± 11 ± 15 MeV/c^2

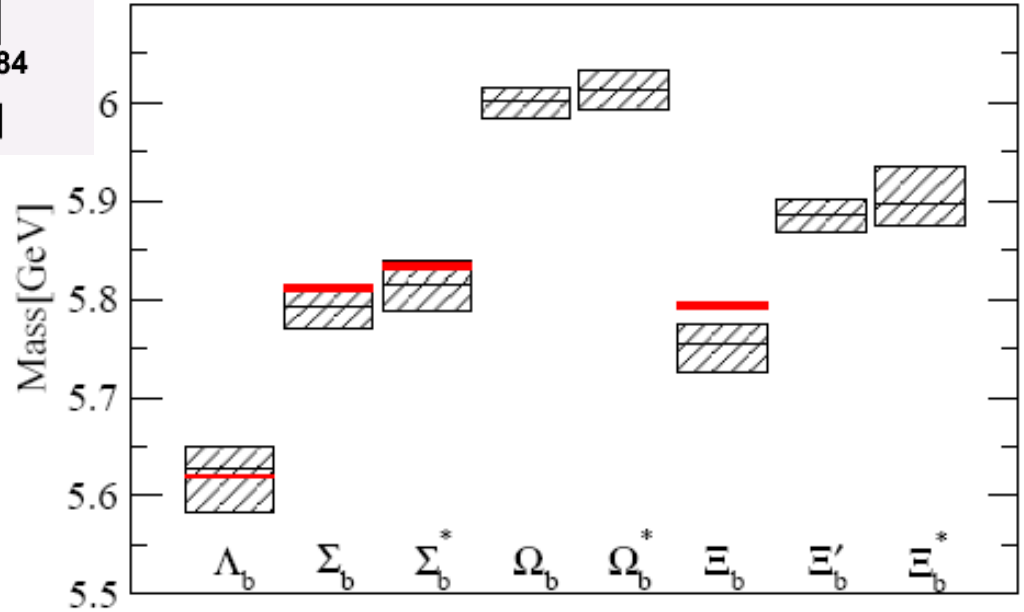
$$\frac{\sigma(\Xi_b^-)\times Br(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b)\times Br(\Lambda_b \to J/\psi\,\Lambda)} = 0.28 \pm 0.09^{+0.09}_{-0.08}$$

Baryon Masses

Color Hyperfine Interaction

$1/m_Q$ and $1/N_c$ Expansion





Lattice NRQCD results
arXiv:0806.4783 hep-lat
June 29, 2008

Conclusions

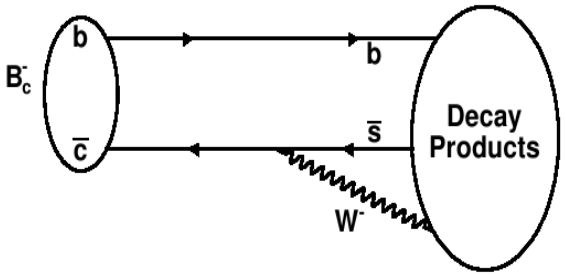
- The Tevatron experiments are very active in B spectroscopy
- Most analyses shown incorporate ~1.3fb^{-1} of data
  - Already have ~4fb^{-1} in the can
  - Expect ~8fb^{-1} before pulling the plug
  - Can expect many improved results and maybe new discoveries in the next two years!

Backup Slides

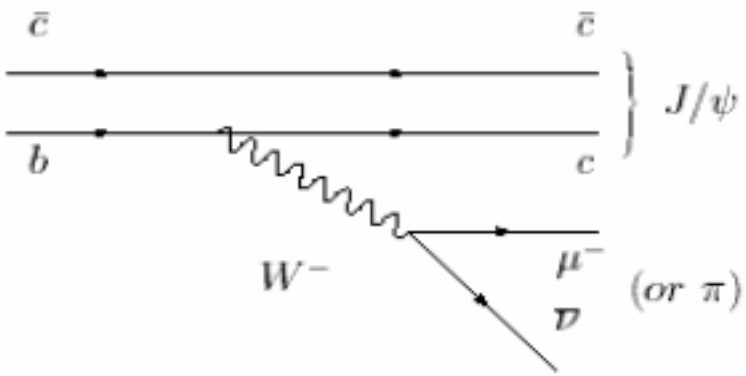
B_c Lifetime

- Decays
  - via b quark:
    - $B_c^+ \rightarrow B_s \pi^+$, $B_s l^+ \nu$
  - via c quark
    - $B_c \rightarrow J/\psi \pi^+$, $J/\psi D_s^+$, $J/\psi l^+ \nu$
  - Annihilation
    - $B_c \rightarrow l^+\nu$

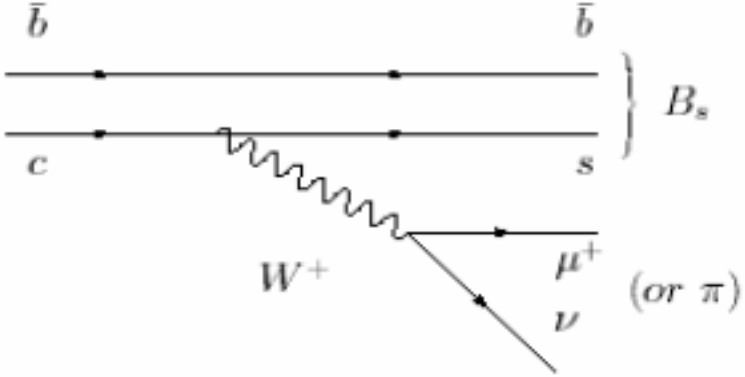
Theory (hep-ph/0308214)
$\tau(B_c)=0.48\pm 0.05$ ps



arXiv:hep-ph/0006104
Phy Rev. D 64, 014003 (2001)
Phy Lett. B 452, 129 (1999)
hep-ph/0002127

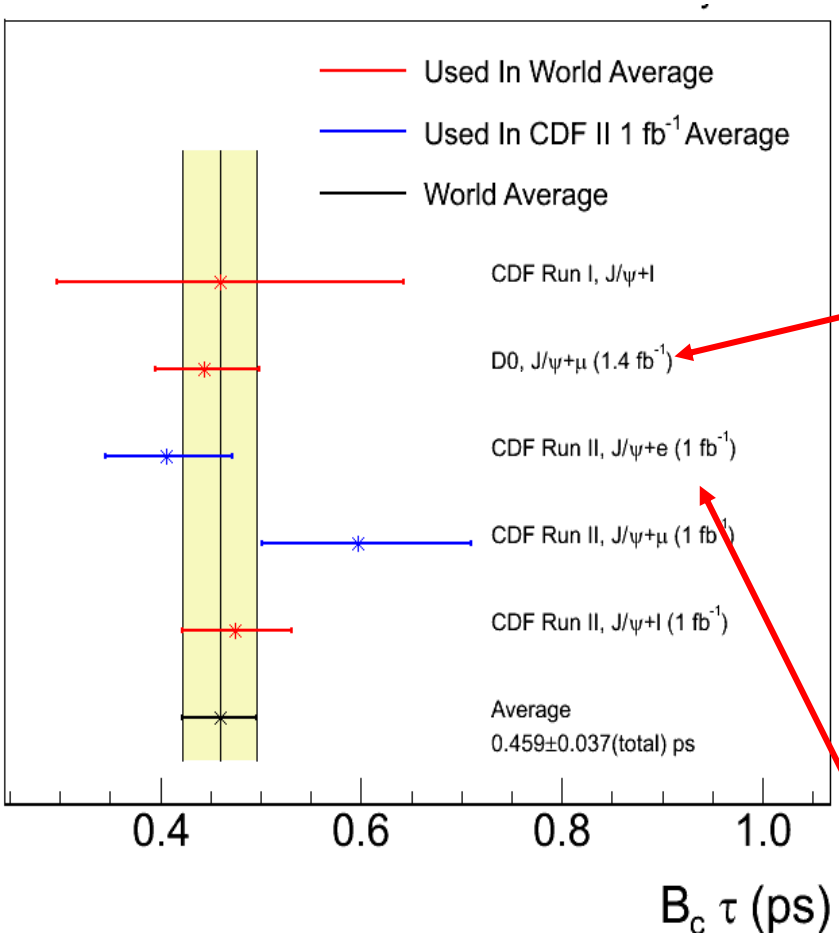


c as spectator (this talk)

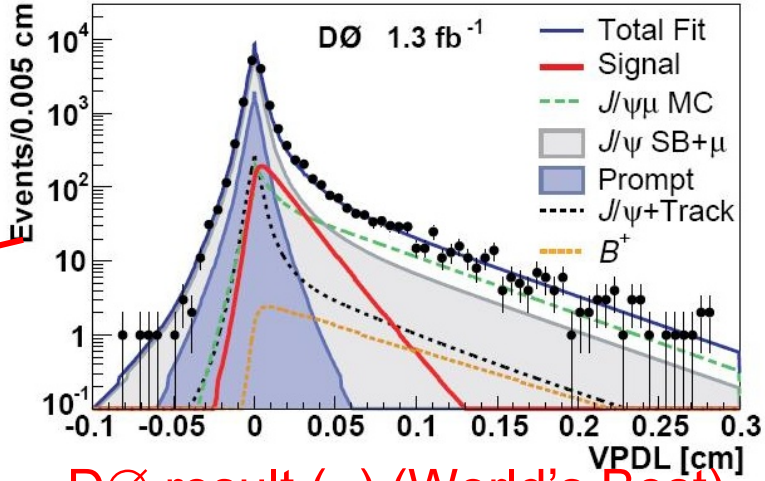


b as spectator (not seen)

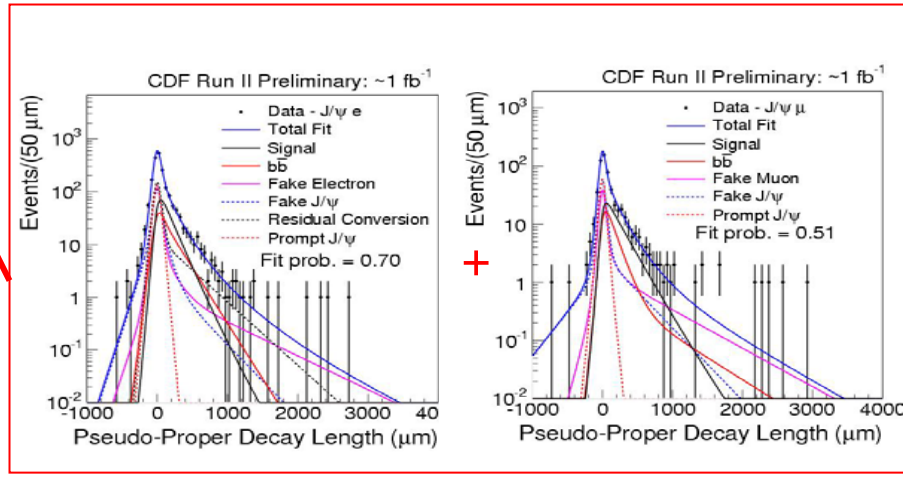
B_c Lifetime



Submitted to PRL



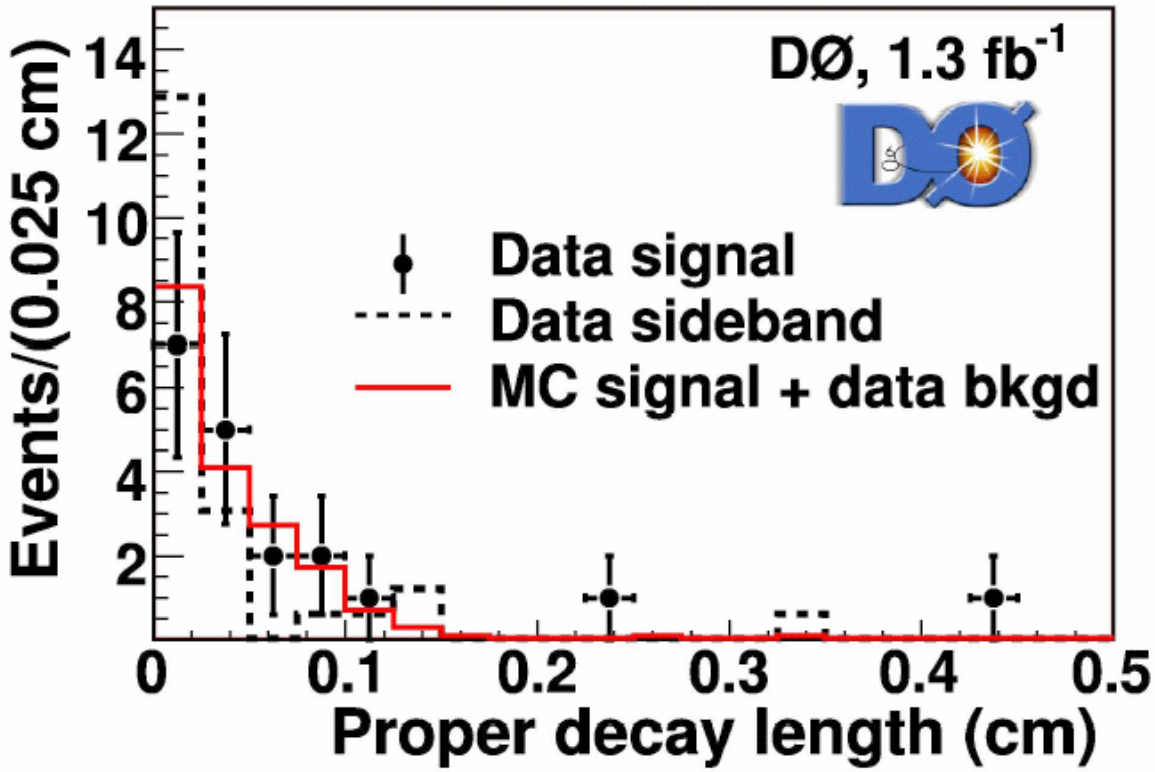
DØ result (μ) (World's Best)



CDF result (e+μ)

Unofficial world average:
τ=0.459±0.037 ps

Ξ_b Lifetime



- Lifetime in agreement with expectations
- A better measurement would be an interesting HQET test