Spectroscopy of hadrons with *b* quarks

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(Representing [mostly] the CDF & DØ Collaborations)

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Motivation

Why *B*-Hadron Spectroscopy?

- Heavy quark hadrons are the "hydrogen atom" of QCD, and *b* hadrons offer the heaviest quarks in bound systems
- Very sensitive tests of potential models, HQET, and all regimes of QCD in general, including lattice gauge calculations

Why at the Tevatron?

- Produce heavier states not accessible anywhere else: B_s^0, B_c, B^{**}, B_s^{**}, Λ_b, Ξ_b, Σ_b ...

  → Complementary to $\Upsilon(4S)$ *B* factories

Motivation

Why *B*-Hadron Spectroscopy?

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Outline: *Heavy Mesons* *Heavy Baryons*

Talks earlier in conf.

$\bar{b}\,s$ $\bar{b}\,s$ $\bar{b}\,c$ $d\,\bar{b}$ $s\,\bar{b}$ $b\,u\,d$ $b\,u\,u$ $b\,s\,d$

$B_s^0,$ $B_s^*,$ $B_c,$ $B^{**},$ $B_s^{**},$ ... $\Lambda_b,$ $\Sigma_b,$ $\Xi_b,$ ...

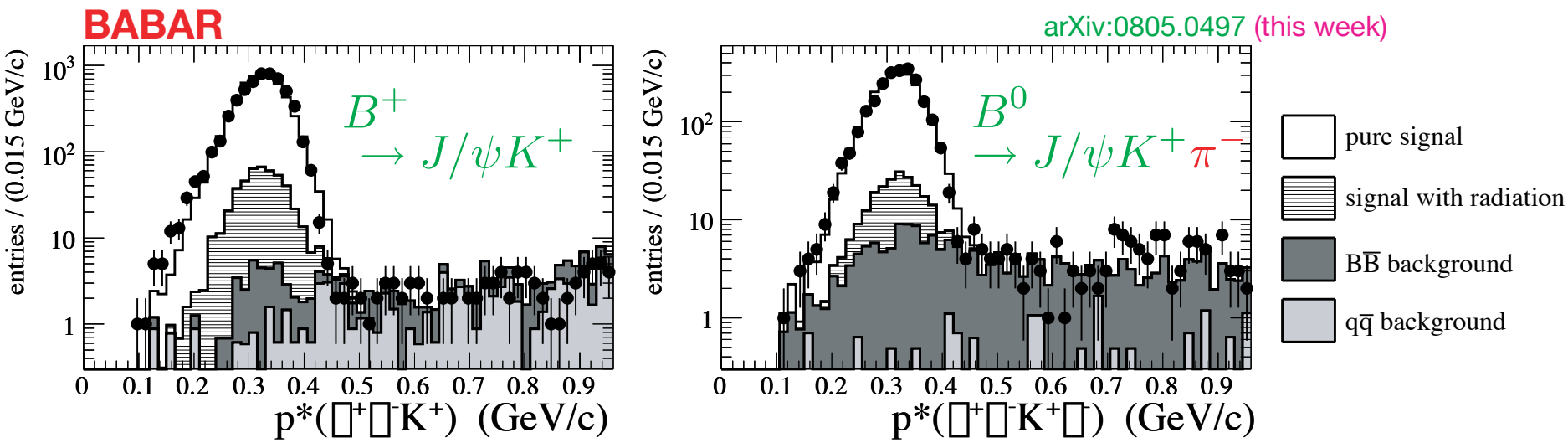
→ Complementary to $\Upsilon(4S)$ *B* factories

$\bar{b}\,d$ $B_d^0,$ B^+ $\bar{b}\,u$

but for completeness...

B^0– B^+ Mass Difference

- Probes size of Coulomb contributions to the quark structure of mesons
- Predictions ~uncertain since contributions from quark-mass difference *m*(*d*) – *m*(*u*) and from Coulomb effects have similar magnitudes and opposite signs



- Compare the two reconstructed momentum distributions

$$\Delta m_B = m(B^0) - m(B^+) = +0.33 \pm 0.05 \pm 0.03\,\mathrm{MeV}$$

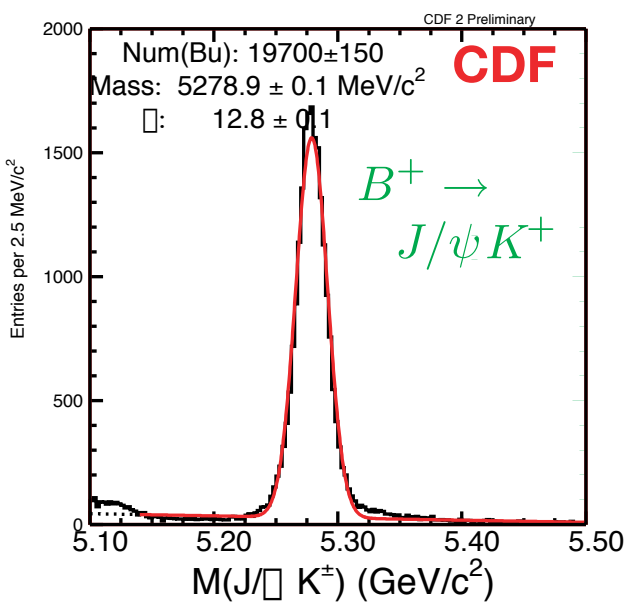
$$+0.37 \pm 0.24\,\mathrm{MeV}$$

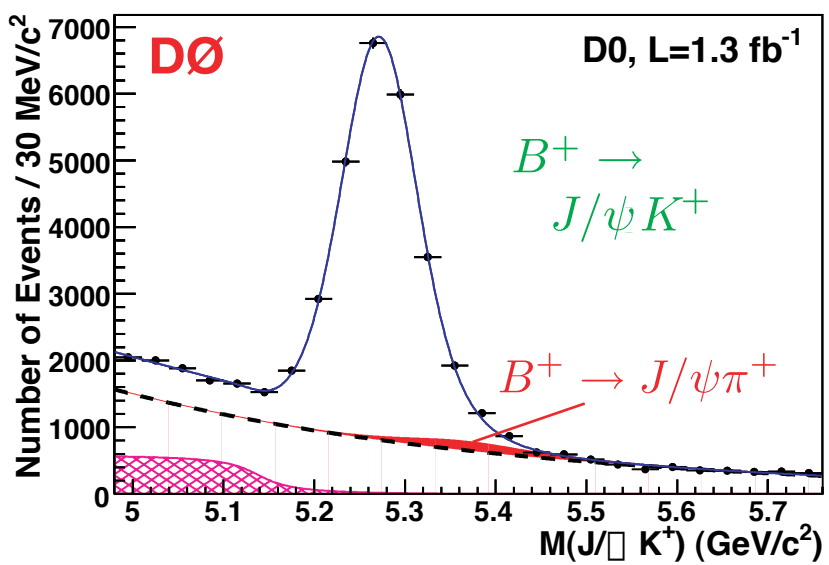
PDG 2007 World Average

B_c Meson

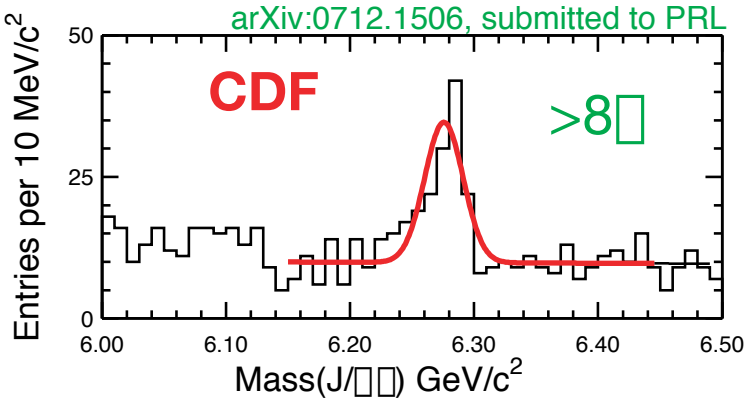
- Unique in that it contains two *different* heavy quarks
- Decays: via b quark $B_c^+ \to B_s^0 \pi^+;\ B_s^0 \ell^+ \nu$
  via c quark $B_c^+ \to J/\psi \pi^+;\ J/\psi D_s^+;\ J/\psi \ell^+ \nu$ — first evidence, but poor mass measurement
  annihilation $B_c^+ \to \ell^+ \nu$
- Expected to have lifetime ~1/3 of other hadrons
  (decay length cuts not as effective at reducing backgrounds)
- Optimize selection critera on control channel $B^+ \to J/\psi K^+$
  similar cuts on $B_c^+ \to J/\psi \pi^+$, take enough data...

$\hookrightarrow \mu^+ \mu^-$
– trigger, mass const.

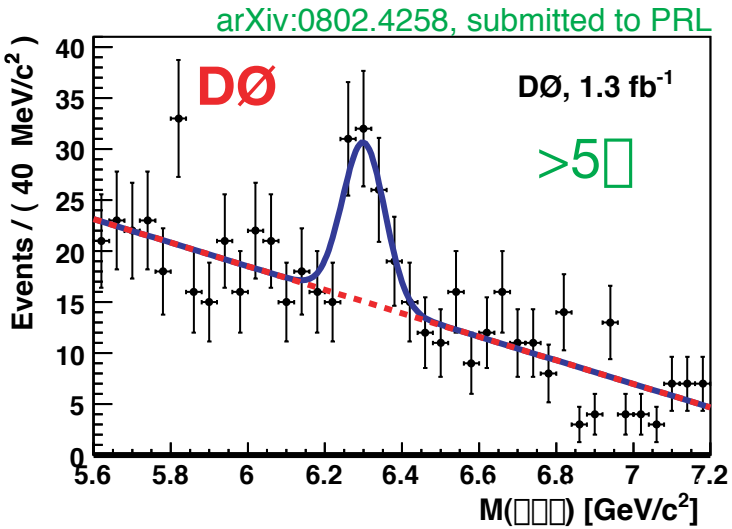




B_c Meson

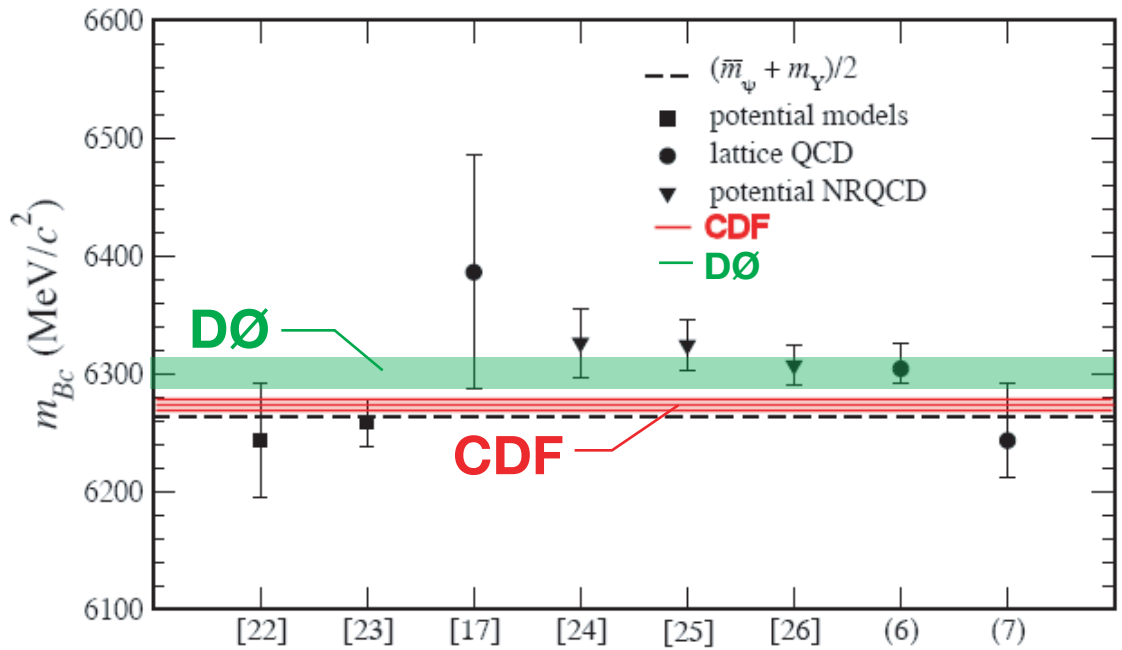


$$m(B_c^+) = 6275.6 \pm 2.9 \pm 2.5\,\mathrm{MeV}$$



$$m(B_c^+) = 6300 \pm 14 \pm 5\,\mathrm{MeV}$$

- Comparison to predictions:

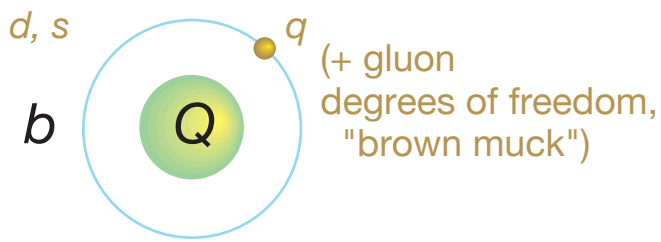


Different models →

- Experimental measurements now smaller undertainty than uncertainties on theoretical predictions

Spectroscopy

Hydrogen atom of strongly interacting systems

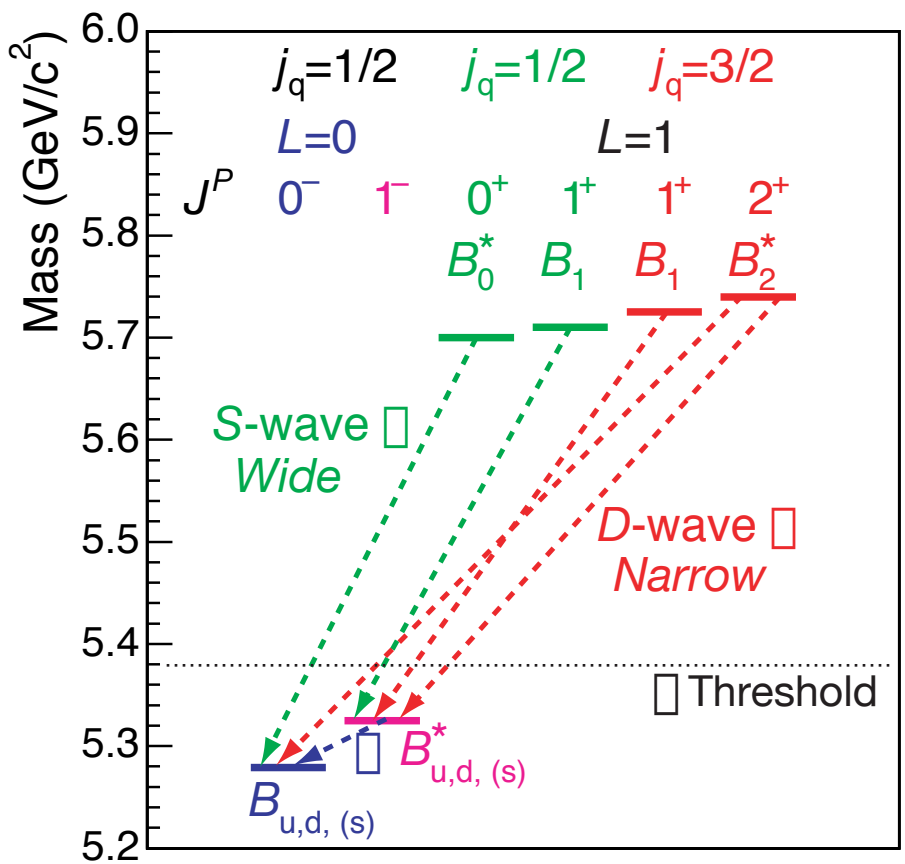


Orbitally Excited *B* Mesons

$L = 1$

$\vec{j}_q = \vec{s}_q + \vec{L}$	$\vec{J} = \vec{s}_Q + \vec{j}_q$		
$j_q = 1/2$	$J = 0, 1$	B_0^*, B_1'	B_{s0}^*, B_{s1}'
$j_q = 3/2$	$J = 1, 2$	B_1, B_2^*	B_{s1}, B_{s2}^*

Collectively referred to as: B^{**} B_J B_s^{**} B_{sJ}

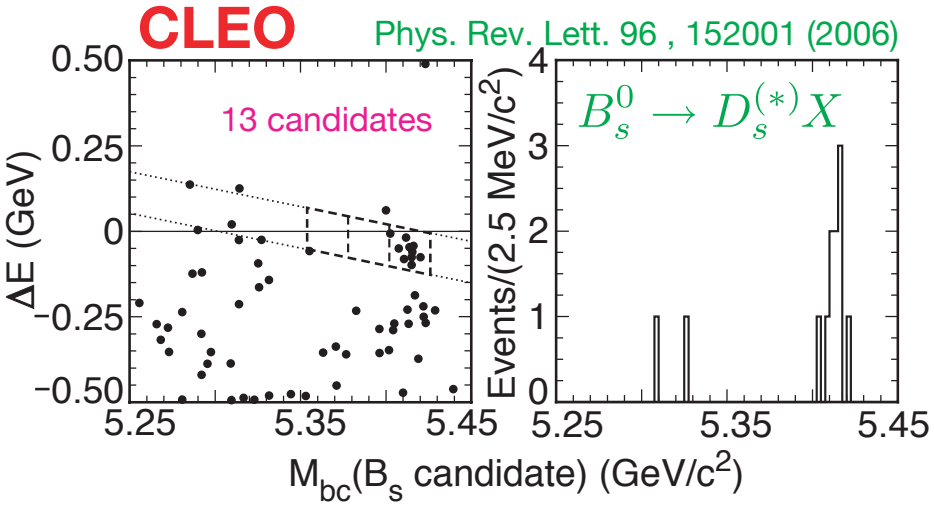


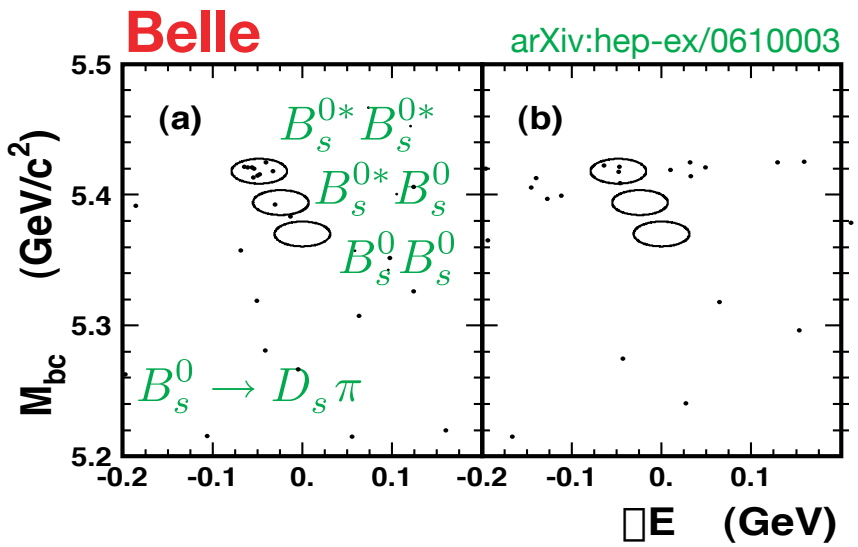
$\cancel{B^0_{(s)1} \to B^+_{(s)}\pi^-}$

forbidden by conservation of parity and angular momentum

but first about that ...

B_s^* State





- Running at the $\Upsilon(5S)$, utilize the beam-constrained invariant mass peak positions for B^{0*} and B_s^{0*}

$$M(B_s^*) = 5411.7 \pm 1.6 \pm 0.6\,\mathrm{MeV}$$
$$\Delta M(B_s^* - B_s) = 45.7 \pm 1.7 \pm 0.7\,\mathrm{MeV}$$

- Similarly, **Belle**

$$M(B_s^*) = 5418 \pm 1 \pm 3\,\mathrm{MeV}$$

1.8□ higher

- My average (including CUSB2 measurement)

$$\uparrow\uparrow_{bs} - \uparrow\downarrow_{bs}$$

$$M(B_s^*) = 5412.8 \pm 0.9\,\mathrm{MeV}$$
$$\Delta M(B_s^* - B_s) = 46.7 \pm 1.0\,\mathrm{MeV}$$

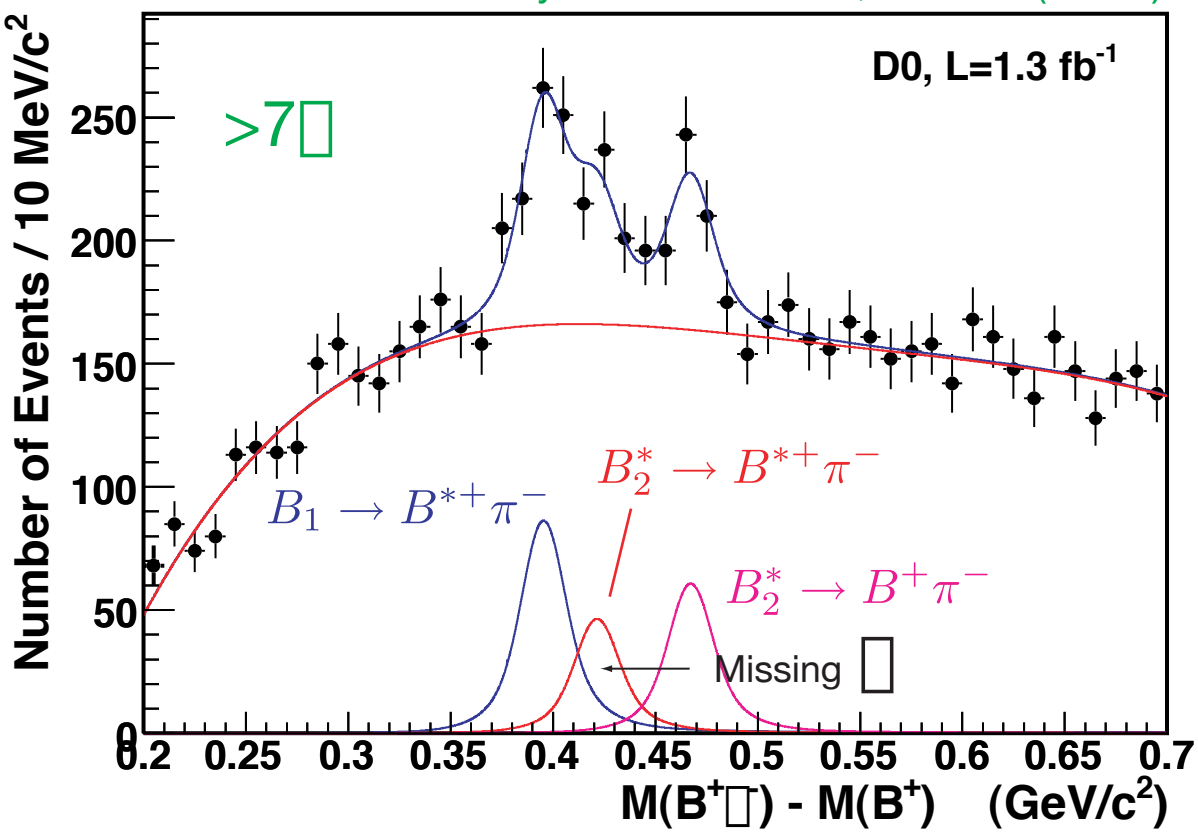
*B*** States

$$B_1 \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^* \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^* \to B^+\pi^-$$

Do not reconstruct

DØ

Phys. Rev. Lett. 99 , 172001 (2007)

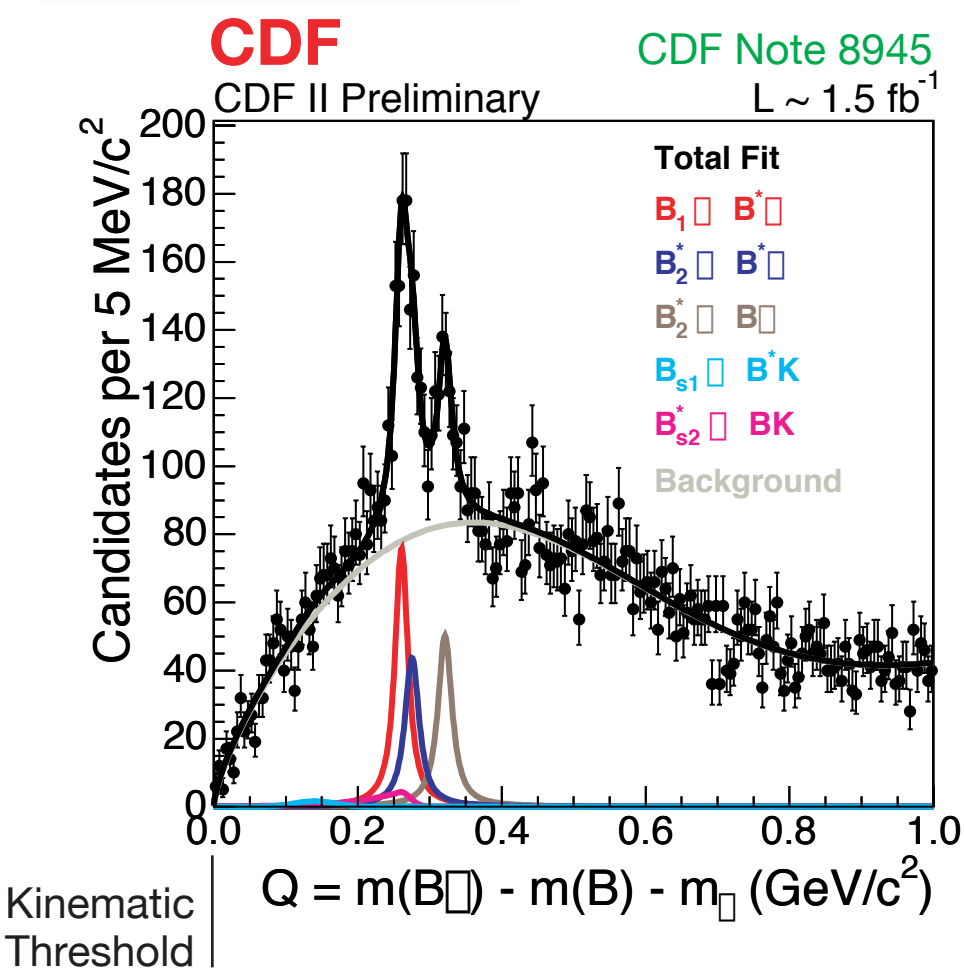


- Reconstruct $B^+ \to J/\psi K^+$ (~23k) then add a pion
- First time these states were separated

$$M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV}$$
$$M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV}$$

*B*** States

$$B_1 \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^* \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^* \to B^+\pi^-$$



- Reconstruct
  $B^+ \to J/\psi K^+$ (~52k)
  CDF adds:
  $B^+ \to D\pi^+$ (~37k)
  $B^+ \to D\pi^+\pi^-\pi^+$ (~10k)
  then add a pion
  (clear peaking structure in each of these 3 channels)

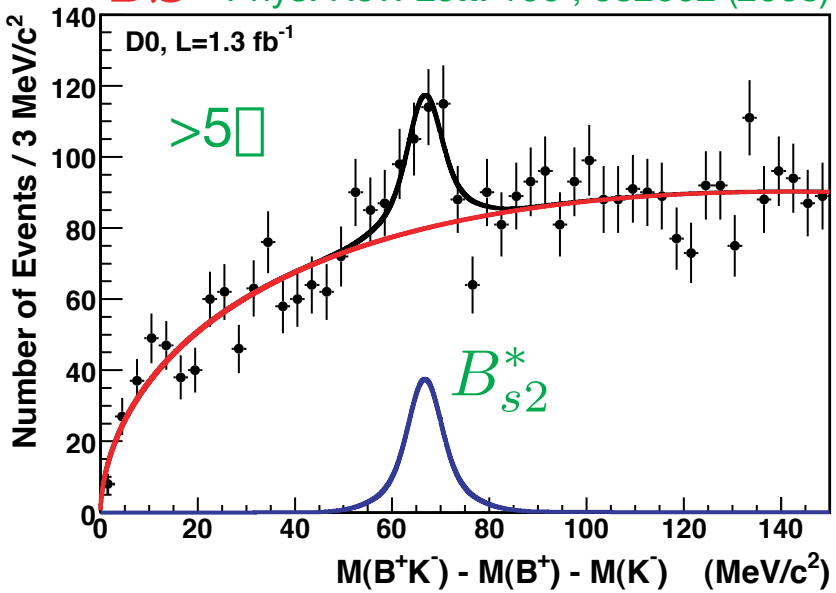
$$\Gamma(B_2^{*0}) = 22.1^{+3.6+3.5}_{-3.1-2.6}\,\mathrm{MeV}$$

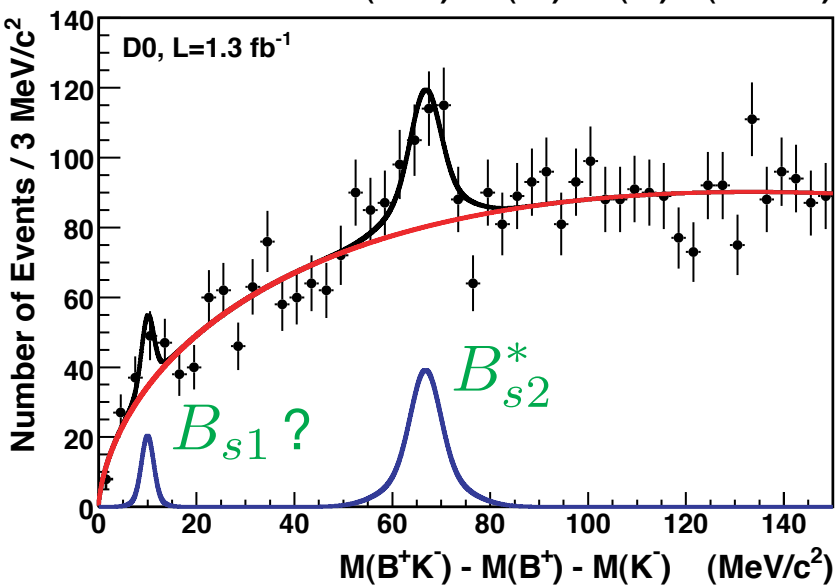
$$M(B_1^0) = 5725.3^{+1.6+0.8}_{-2.1-1.1}\,\mathrm{MeV}$$
$$M(B_2^{*0}) = 5739.9^{+1.7+0.5}_{-1.8-0.6}\,\mathrm{MeV}$$

B_s^{**} States

$$B_{s1} \to B^{*+} K^- ;\ B^{*+} \to B^+ \gamma$$
$$B_{s2}^* \to B^{*+} K^- ;\ B^{*+} \to B^+ \gamma$$
$$B_2^* \to B^+ K^-$$

DØ Phys. Rev. Lett. 100 , 082002 (2008)





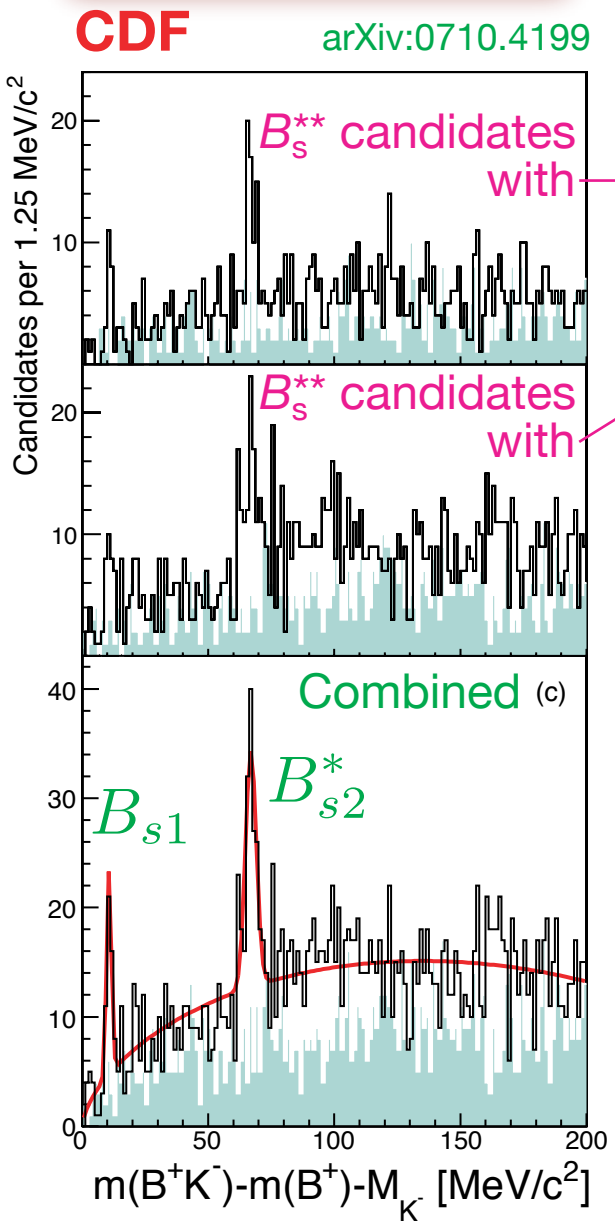
- Reconstruct $B^+ \to J/\psi K^+$ add a kaon instead of pion

$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7\,\mathrm{MeV}$$

- Try fitting for B_{s1} ; statistical significance is less than 3 . Hence with the current data, the existence of a B_{s1} state can be neither confirmed nor excluded.
- This close to threshold, would expect heavy (factor ~0.074) phase-space suppression

B_s^{**} States

$$B_{s1} \to B^{*+}K^-;\ B^{*+} \to B^+\gamma$$
$$B_{s2}^* \to B^{*+}K^-;\ B^{*+} \to B^+\gamma$$
$$B_2^* \to B^+K^-$$



- Reconstruct $B^+ \to J/\psi K^+$

  CDF adds: $B^+ \to D\pi^+$

  then add a kaon (instead of a pion)
  (two peaks in each of these two channels)

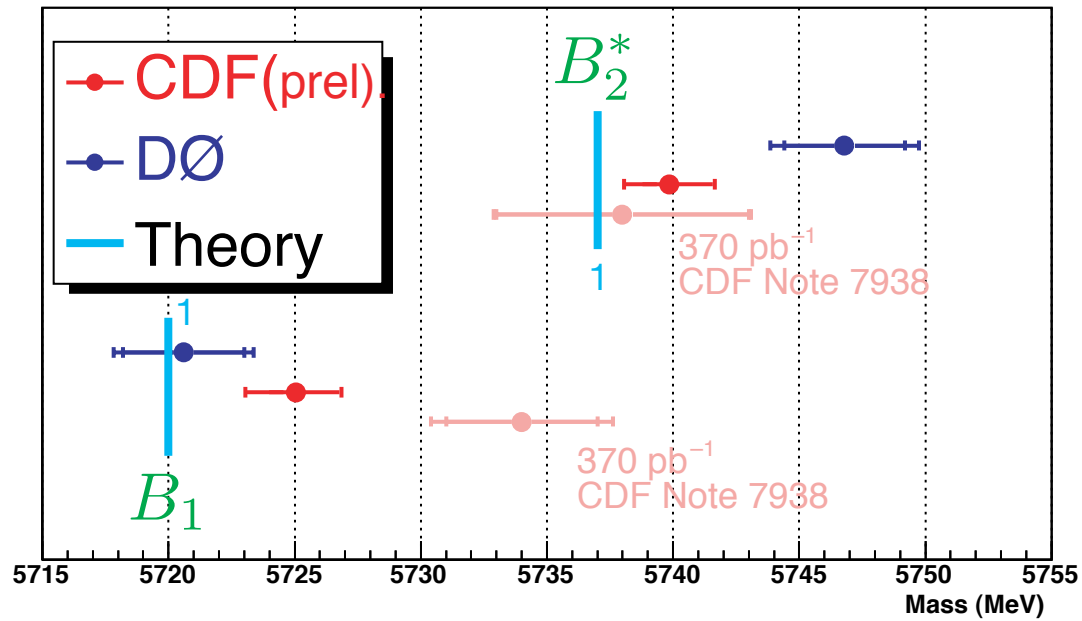
- First evidence of narrow B_{s1} state

$$M(B_{s1}) = 5829.4 \pm 0.21 \pm 0.14 \pm 0.6\,(\mathrm{PDG})\,\mathrm{MeV}$$
$$M(B_{s2}^*) = 5839.6 \pm 0.39 \pm 0.14 \pm 0.5\,(\mathrm{PDG})\,\mathrm{MeV}$$

$B^{**}_{(s)}$ Summary

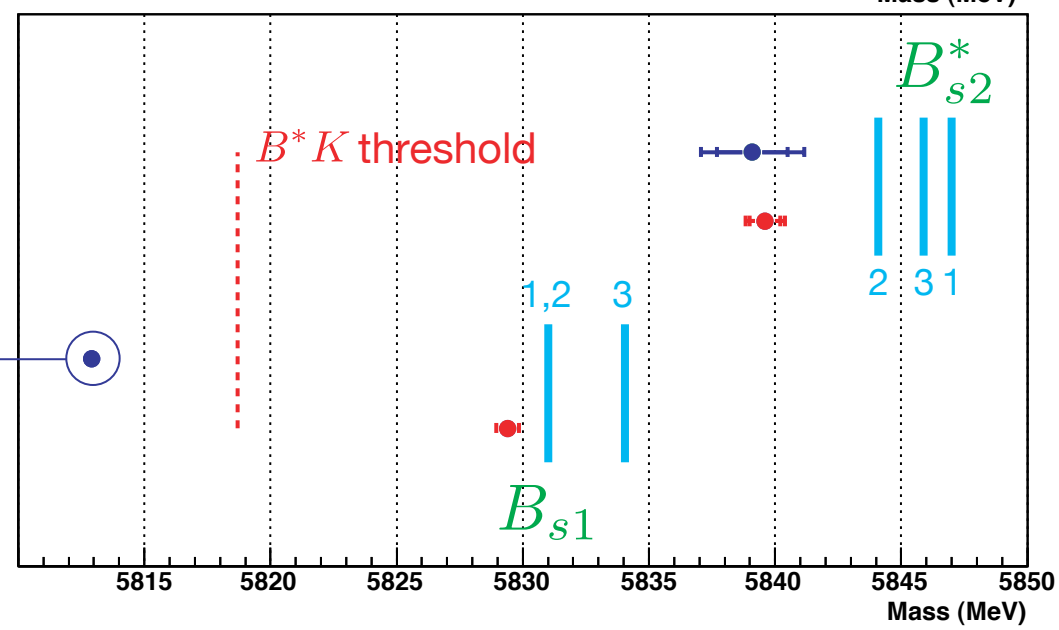
Theory: 1. Matsuki et al., hep-ph/0605019
2. Ebert et al., PRD 57, 5663;
3. Eichen et al., PRL 71, 4116

Phys. Rev. Lett. 99, 172001 (2007)
CDF Public Note 8945

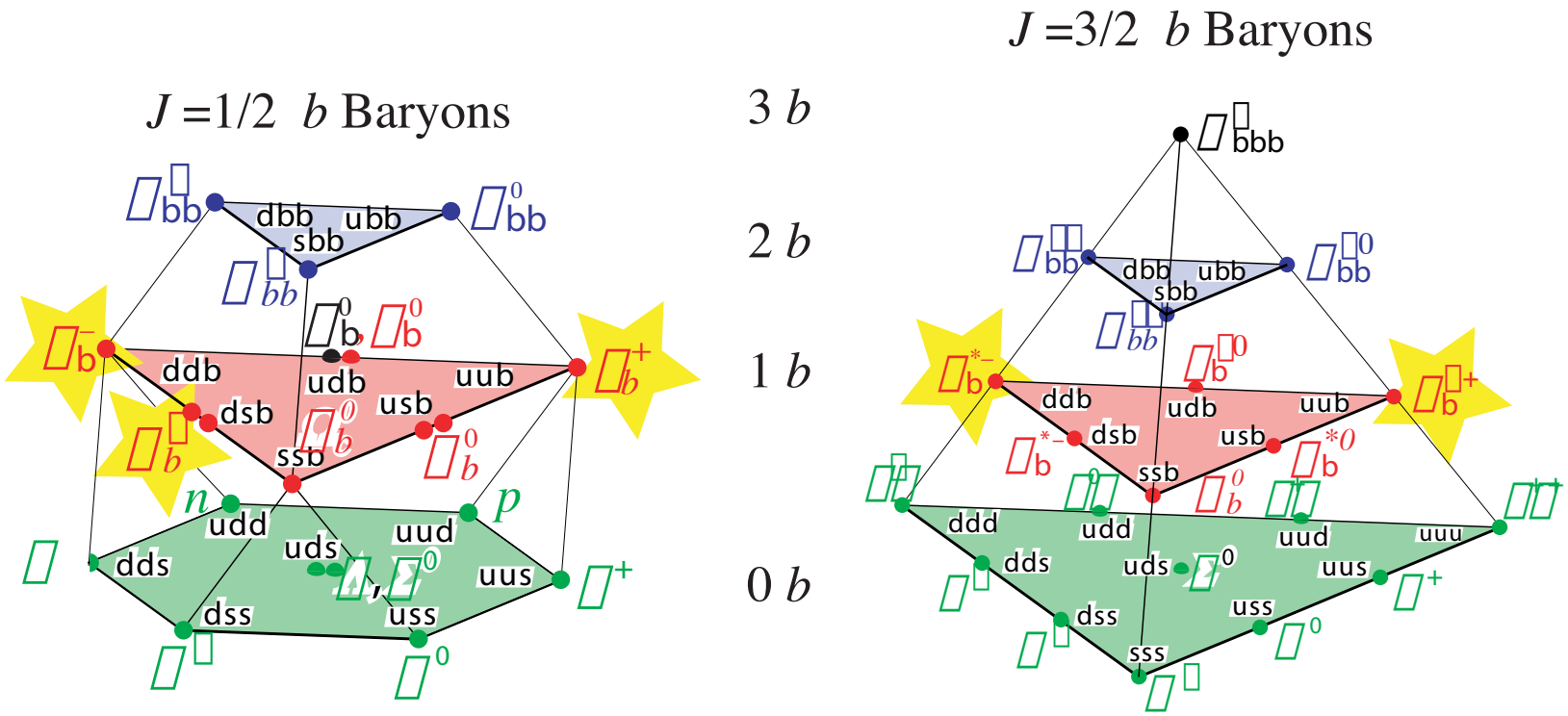


Phys. Rev. Lett. 100, 082002 (2008)
Phys. Rev. Lett. 101, 082002 (2008)

Predicted from DØ $\Delta M(B^{**})$



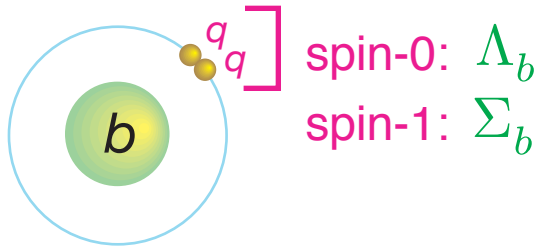
New *b*-Flavored Baryons



- Until recently, ground state Λ_b was the only directly observed *b* baryon
- More statistics, look for other *b* baryon states

Σ_b Heavy Baryon

L=0 "atomic" system,
heavy quark and light *diquark*



$\Sigma_b^{(*)+}$: *buu*

$\Sigma_b^{(*)-}$: *bdd*

~~$\Sigma_b^{(*)0}$: *bud*~~

$\Sigma^{(*)0} \to \Lambda_b^0 \pi^0$
tough at Tevatron

Σ_b: *bqq*

$$J^P = S_Q + s_{qq}$$

$= 3/2^+$: Σ_b^*

$= 1/2^+$: Σ_b

- Predictions from HQET,Lattice QCD, potential models, sum rules:

	Property	Expected Values (MeV/c^2)
Diquark spin alignment	$m(\Sigma_b) - m(\Lambda_b^0)$	$180 - 210$
Hyperfine mass splitting	$m(\Sigma_b^*) - m(\Sigma_b)$	$10 - 40$
Isospin (*u, d* diff.)	$m(\Sigma_b^-) - m(\Sigma_b^+)$	$5 - 7$
	$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim 8, \sim 15$

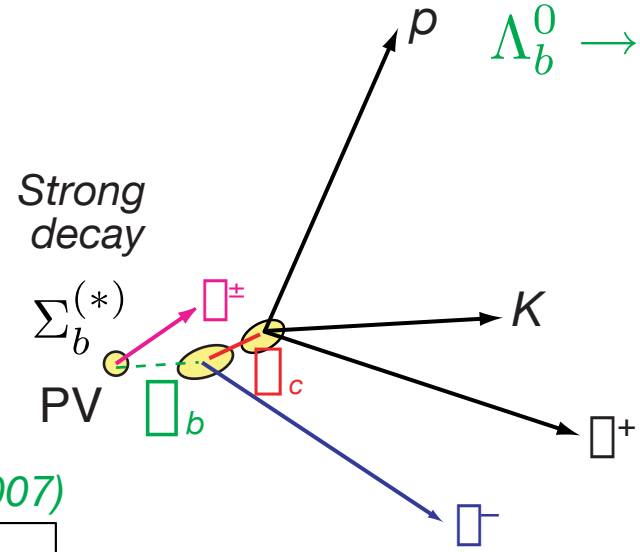
Λ_b Heavy Baryon

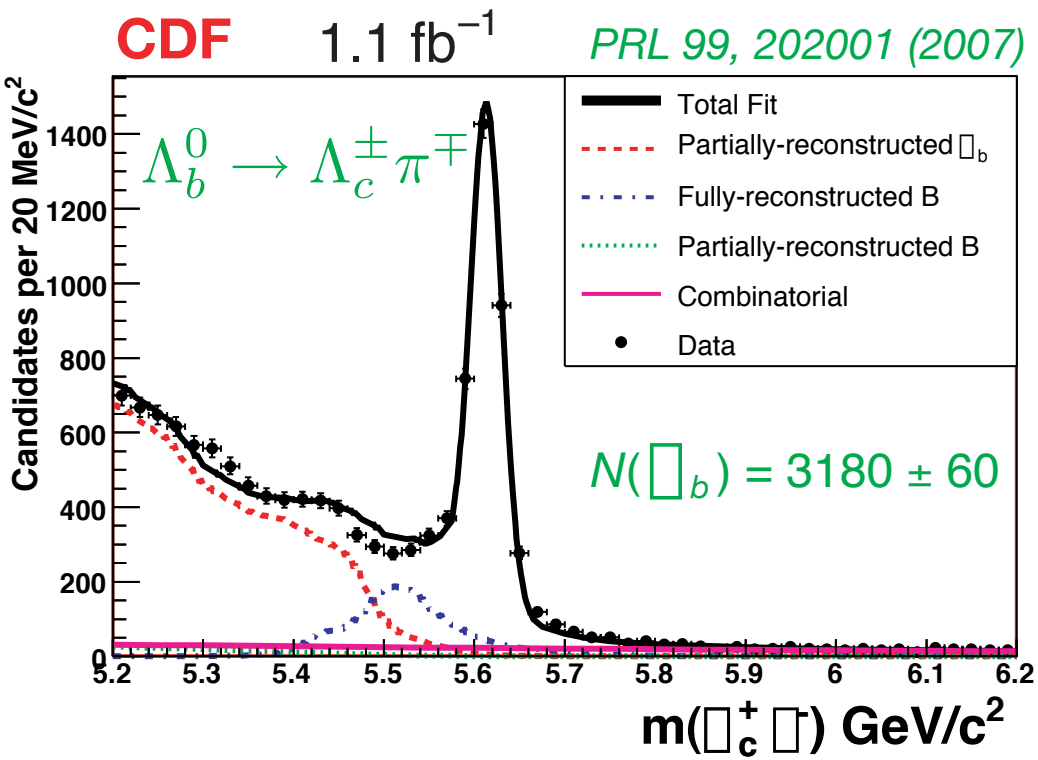
$\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm;$

$\Lambda_b^0 \to \Lambda_c^\pm \pi^\mp;$

$\Lambda_c \to pK\pi$

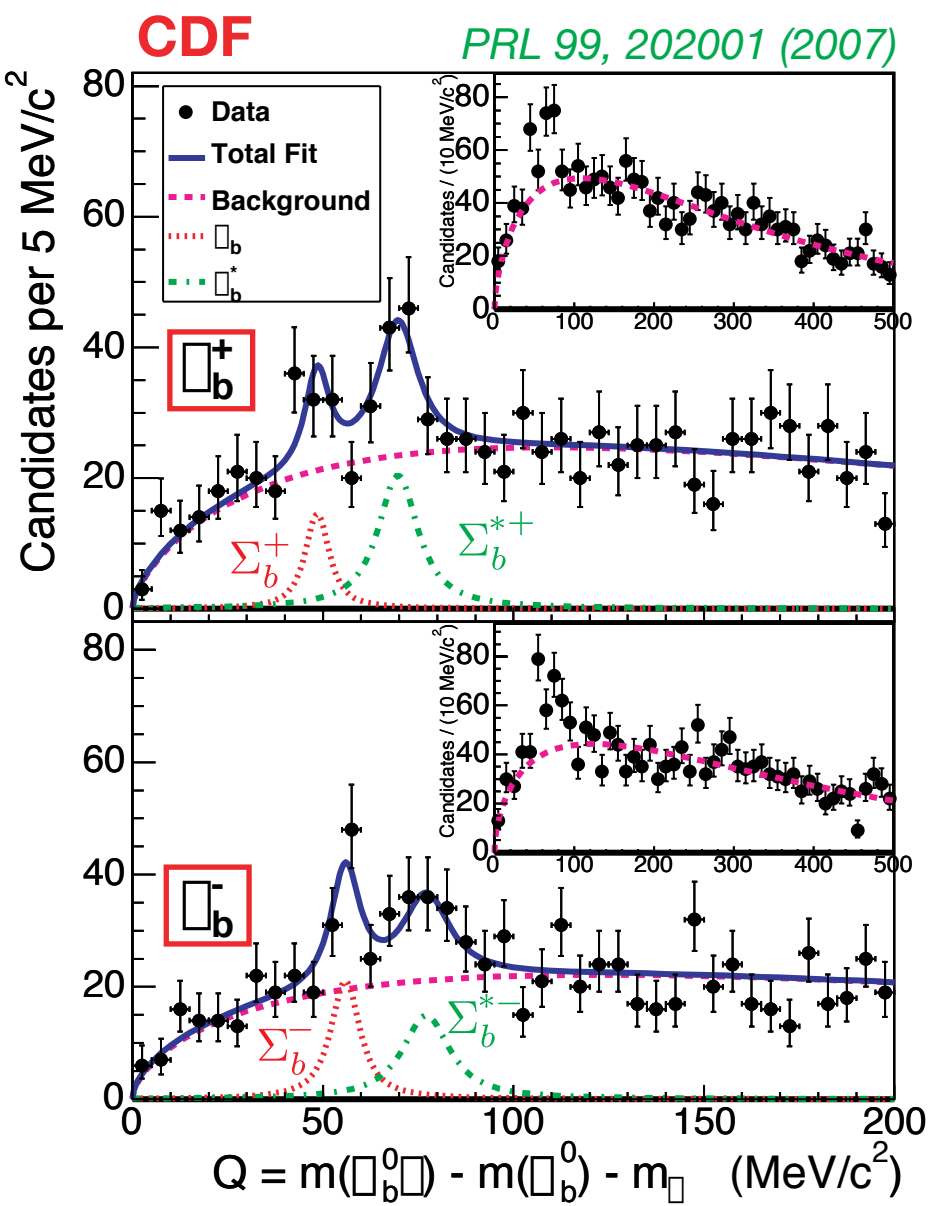
- Form a large optimized sample of $\Lambda_b^0 \to \Lambda_c^\pm \pi^\mp$





- Then add a pion
- Estimate backgrounds:
  - Λ_b^0 with random hadronization tracks (89%)
  - other b hadrons (~7%)
  - combinatorics (~3%)
- Fit for *Q* values and no. of events

Σ_b Heavy Baryon



- Constrain $m(\Sigma_b^{*+}) - m(\Sigma_b^+) = m(\Sigma_b^{*-}) - m(\Sigma_b^-)$
- Two peaks for each charge, 5.2σ significance w.r.t. no signal
- Use CDF II measurement of $m(\Lambda_b^0) = 5619.7 \pm 1.2 \pm 1.2\,\mathrm{MeV}$ to get absolute masses:

$$m(\Sigma_b^+) = 5807.8^{+2.0}_{-2.2} \pm 1.7\,\mathrm{MeV}$$
$$m(\Sigma_b^-) = 5815.2 \pm 1.0 \pm 1.7\,\mathrm{MeV}$$
$$m(\Sigma_b^{*+}) = 5829.0^{+1.6+1.7}_{-1.8-1.8}\,\mathrm{MeV}$$
$$m(\Sigma_b^{*-}) = 5836.4 \pm 2.0^{+1.8}_{-1.7}\,\mathrm{MeV}$$

Λ_b Heavy Baryon

- Splittings?

	Property	Values (MeV/c^2) Expected	Measured (CDF)
Diquark spin alignment	$m(\Sigma_b^+) - m(\Lambda_b^0)$	$180 - 210$	$188.1^{+2.0+0.2}_{-2.2-0.3}$ *
	$m(\Sigma_b^-) - m(\Lambda_b^0)$	$180 - 210$	$195.5 \pm 1.0 \pm 0.2$ *
Hyperfine mass splitting	$m(\Sigma_b^*) - m(\Sigma_b)$	$10 - 40$	$21.1^{+2.0+0.4}_{-1.9-0.3}$
Isospin (*u*, *d* diff.)	$m(\Sigma_b^-) - m(\Sigma_b^+)$	$5 - 7$	$7.4^{+2.2}_{-2.4}$ *
	$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim 8, \sim 15$	

PRL 99, 202001 (2007)

* *Speaker's calc.*

Σ_b Heavy Baryon

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Diquark spin alignment	$m(\Sigma_b^+) - m(\Lambda_b^0)$	$180 - 210$	$188.1^{+2.0+0.2}_{-2.2-0.3}$ *
	$m(\Sigma_b^-) - m(\Lambda_b^0)$	$180 - 210$	$195.5 \pm 1.0 \pm 0.2$ *
(Isospin averaged)	$m(\Sigma_b) - m(\Lambda_b^0)$	194 [1]	192
Hyperfine mass splitting	$m(\Sigma_b^*) - m(\Sigma_b)$	$10 - 40$	$21.1^{+2.0+0.4}_{-1.9-0.3}$
	$m(\Sigma_b^*) - m(\Sigma_b)$	20.0 ± 0.3 [2]	
Isospin (*u*, *d* diff.)	$m(\Sigma_b^-) - m(\Sigma_b^+)$	$5 - 7$	$7.4^{+2.2}_{-2.4}$ *
	$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim 8, \sim 15$	

PRL 99, 202001 (2007)

[1] Karliner, Lipkin, hep-ph/0307243, PLB 600 (2008) 539

[1] Karliner, Lipkin, arXiv:0804.1575

Ξ_b Heavy Baryon

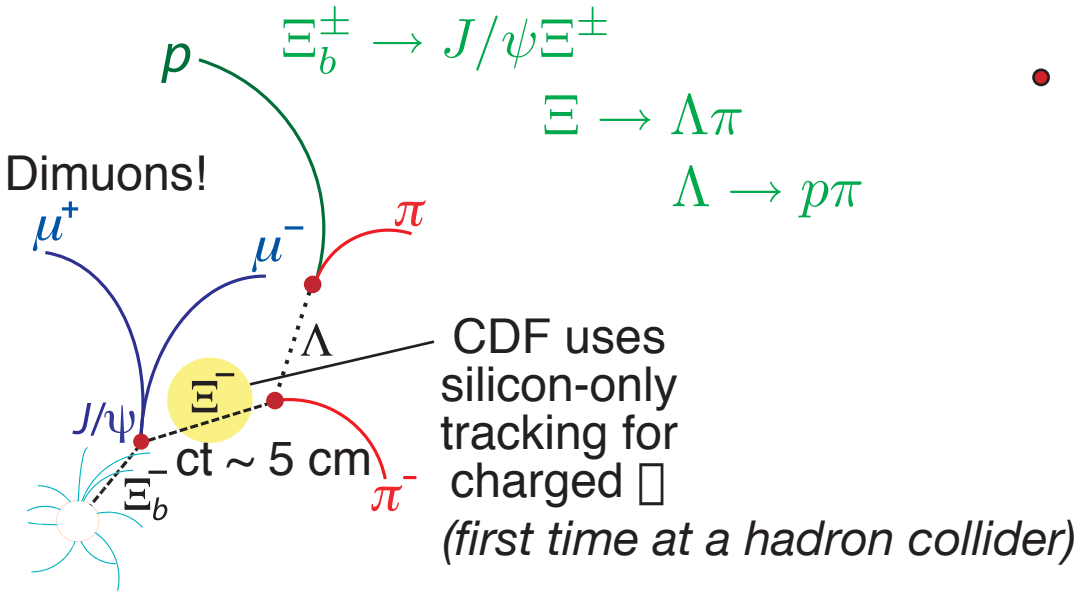
"Strangely Beautiful Baryon"
"Triple Scoop Baryon"

- Quark content: ~~Ξ_b^0 : *bsu*~~ $\Xi_b^0 \to \Xi_c^0 \pi^0$ $\Xi_b^0 \to D^0 \Lambda$

  Ξ_b^- : *bsd* $\Xi_b^\pm \to J/\psi \Xi^\pm$ $\Xi_b^\pm \to \Xi_c^0 \pi^\pm$

  CDF, DØ CDF

- Decays weakly, dominated by *b* quark
  - Lifetime should be comparable to other *b* hadrons
  - DELPHI measured $\tau(\Xi_b) = 1.39^{+0.34}_{-0.28}\,\mathrm{ps}$ from excess of $\Xi^- \ell^- \nu_\ell X$ events



- Challenging for track reco.
  - DØ reprocesses tracks using special settings to improve effic. of high-impact parameter tracks
  - CDF vertexing software needed modifications

Ξ_b Heavy Baryon

"Strangely Beautiful Baryon"
"Triple Scoop Baryon"

- Quark content: Ξ_b^0 : ~~*bsu*~~ $\Xi_b^0 \to \Xi_c^0 \pi^0$ $\Xi_b^0 \to D^0 \Lambda$
  Ξ_b^- : *bsd* $\Xi_b^\pm \to J/\psi \Xi^\pm$ $\Xi_b^\pm \to \Xi_c^0 \pi^\pm$
  CDF, DØ CDF
- Decays weakly, dominated by *b* quark
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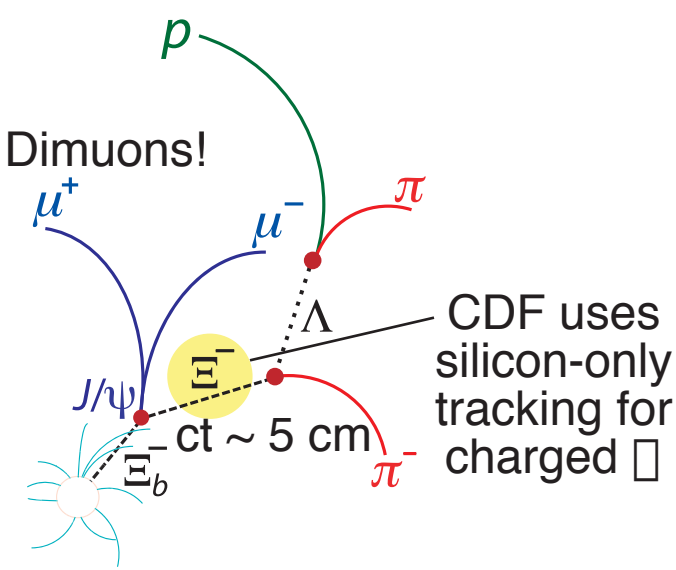
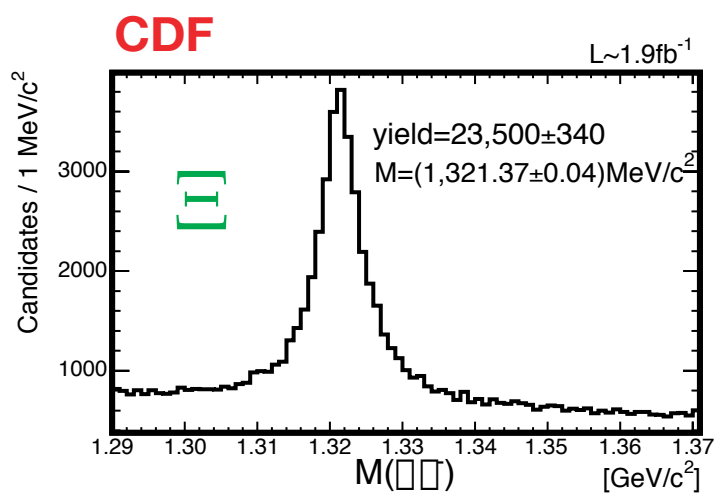
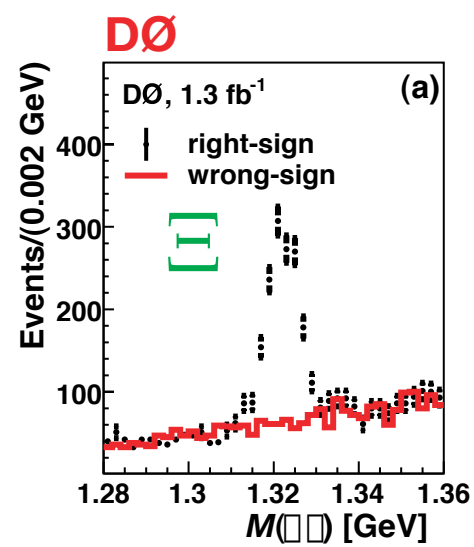




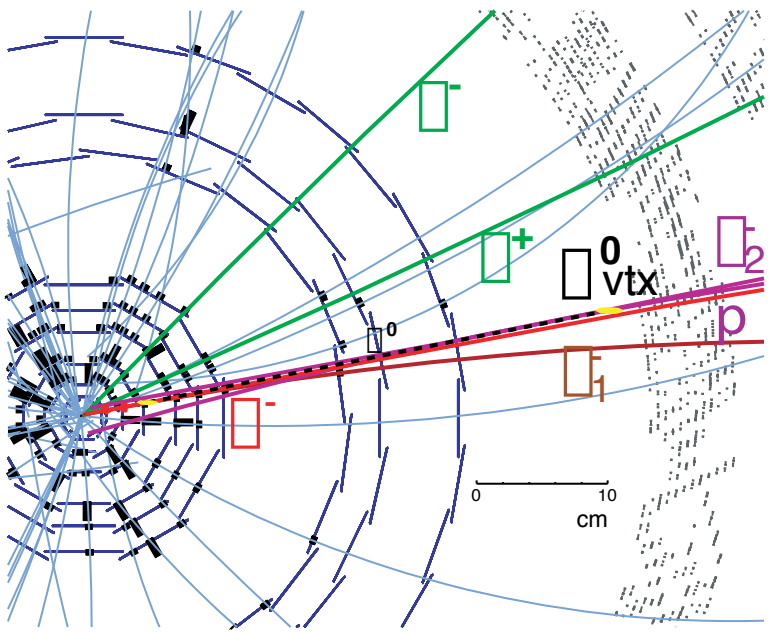


Λ_b Heavy Baryon

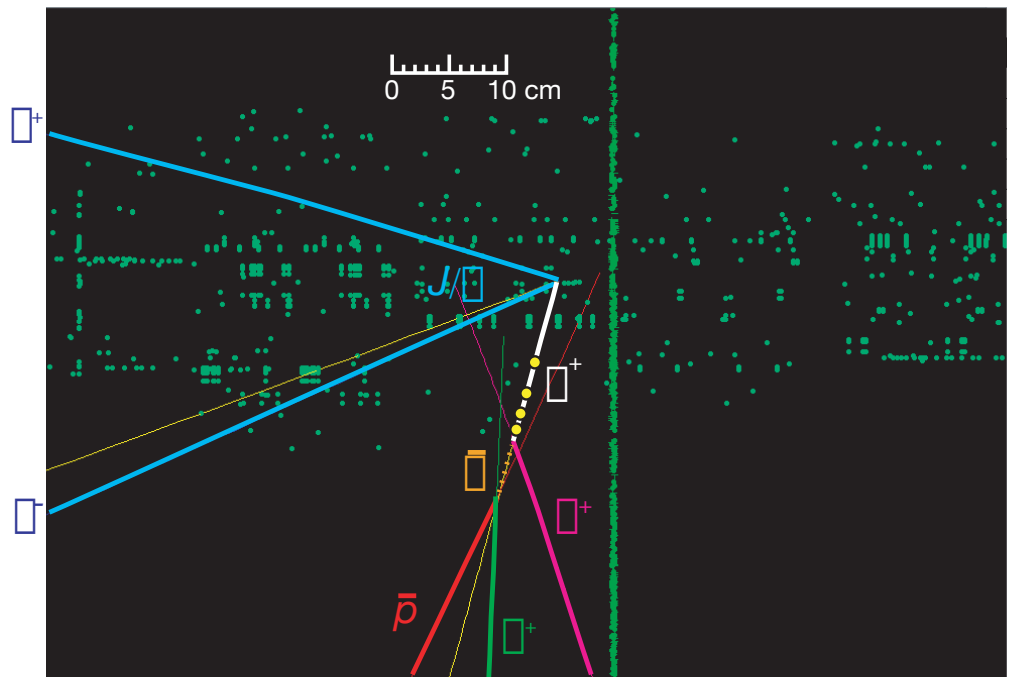
"Strangely Beautiful Baryon"
"Triple Scoop Baryon"

- Selection: cuts on momenta, vertex quality, *decay length*
- DØ: based on wrong-sign data, signal MC
- CDF: use $B^+ \to J/\psi K^+$ as control sample, replace K with Λ

CDF

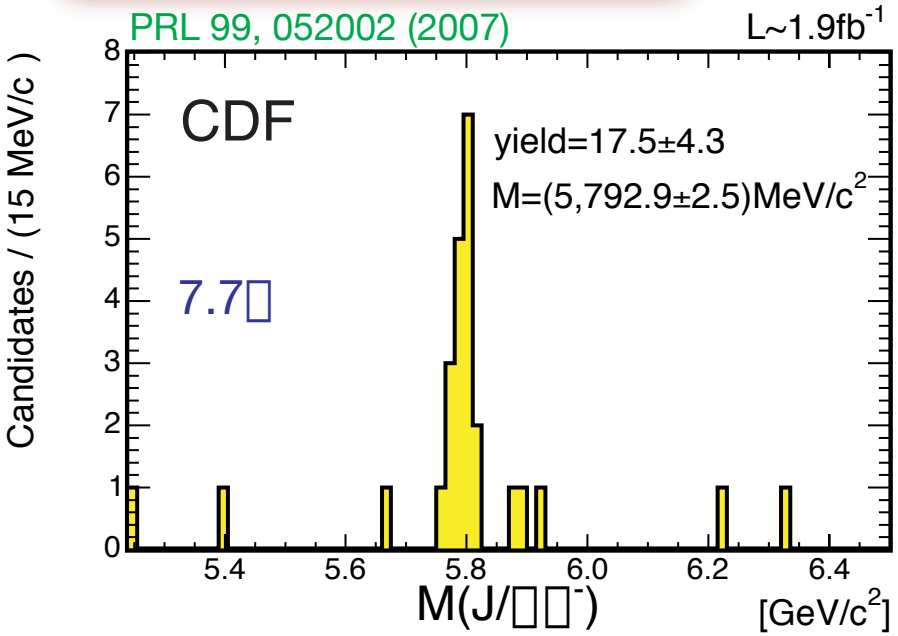


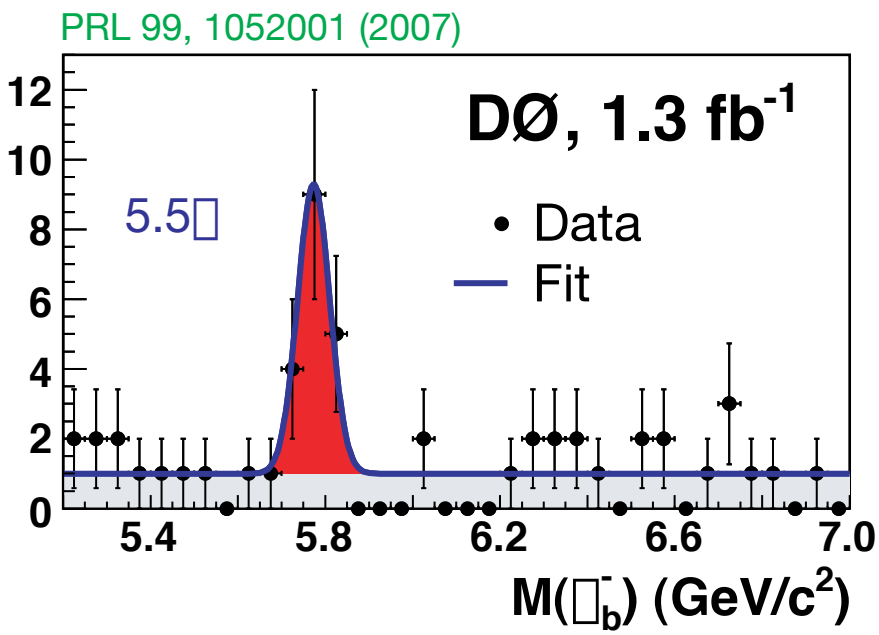
DØ



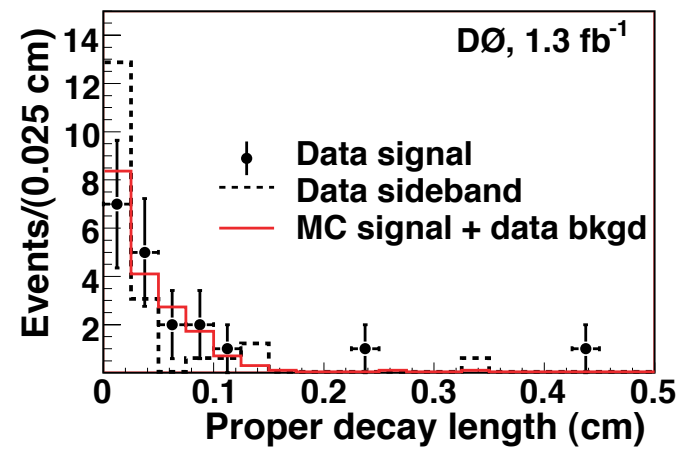
Run 179200, Event 55278820, $M(\Lambda_b)$ = 5.788 GeV

□b Heavy Baryon





- DØ: many checks that no signal in wrong-sign $\Lambda\pi$ comb., Ξ sidebands, J/ψ sidebands
- CDF also has signal in $\Xi_b^{\pm} \to \Xi_c^0 \pi^{\pm}$ channel
- DØ: lifetime consistent with expectations:



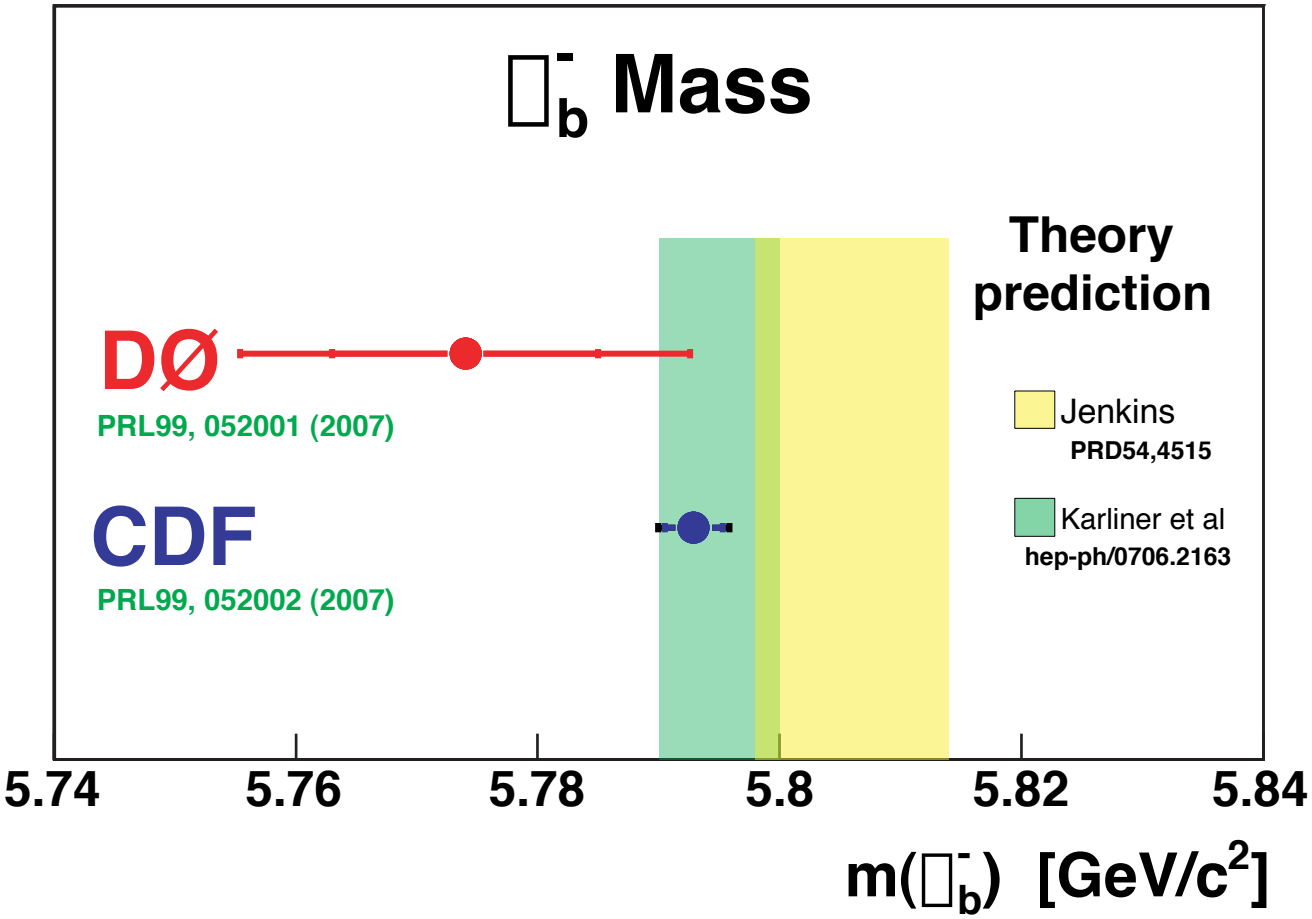
CDF

$$M(\Xi_b) = 5792.9 \pm 2.4 \pm 1.7\,\mathrm{MeV}$$

DØ

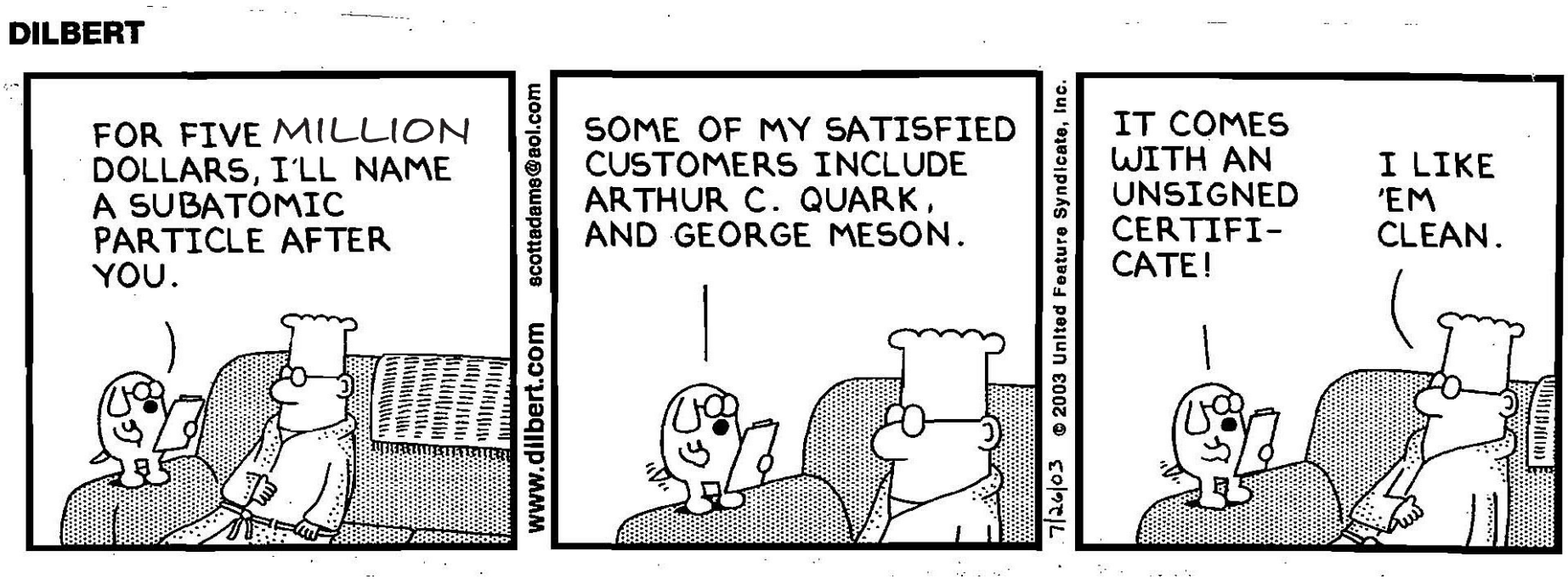
$$M(\Xi_b) = 5774 \pm 11 \pm 15\,\mathrm{MeV}$$

Ω_b Heavy Baryon



Conclusions & Prospects

- Renaissance of spectroscopy (and properties) as new heavy states continue to be discovered
- Match of data to theory predictions for most *B* mesons is good; less so for the orbitally excited B^{**} and B_s^{**} states
- Excellent data-theory agreement for new heavy *b* baryons
- Providing useful input and comparisons to potential models, HQET, lattice gauge calculations, other QCD models: outstanding prospects for continued *precision* predictions (e.g., $\Sigma_b^{(*)}$ inputs for Ξ_b)
- Next good experimental prospects? Possibility of $\Omega_b \to J/\psi\Omega$, $\Xi_{bc} \to J/\psi\Lambda_c$, $\Xi_b^0 \to \Xi_c^+\pi^-$ among others...
- Tevatron doing very well, expect to at least *double* our data-set to ~6 – 8 fb^{-1} by the end of running in 2009 – 2010

Conclusions & Prospects

- Having trouble finding new names for new states (*X, Y, Z...?*)?