Spectroscopy of hadrons with *b* quarks

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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

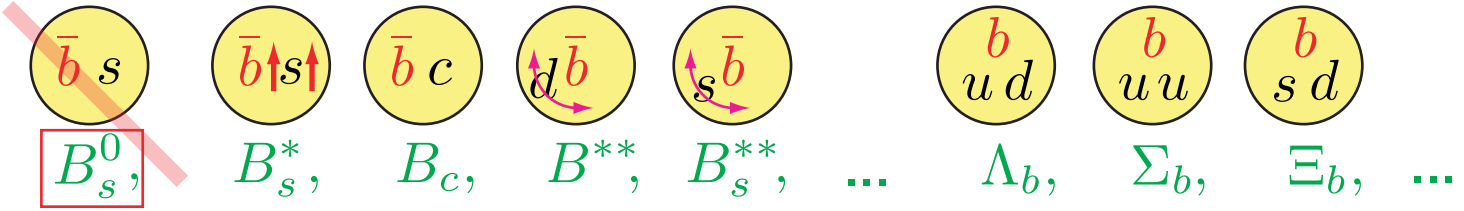
Motivation

Why *B*-Hadron Spectroscopy?

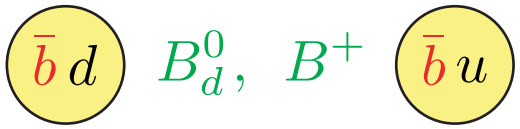
- Heavy quark hadrons are the "hydrogen atom" of QCD, and *b* hadrons offer the heaviest quarks in bound systems
- Very sensitive tests of potential models, HQET, and all regimes of QCD in general, including lattice gauge calculations

Outline: *Heavy Mesons* *Heavy Baryons*

Talks earlier in conf.



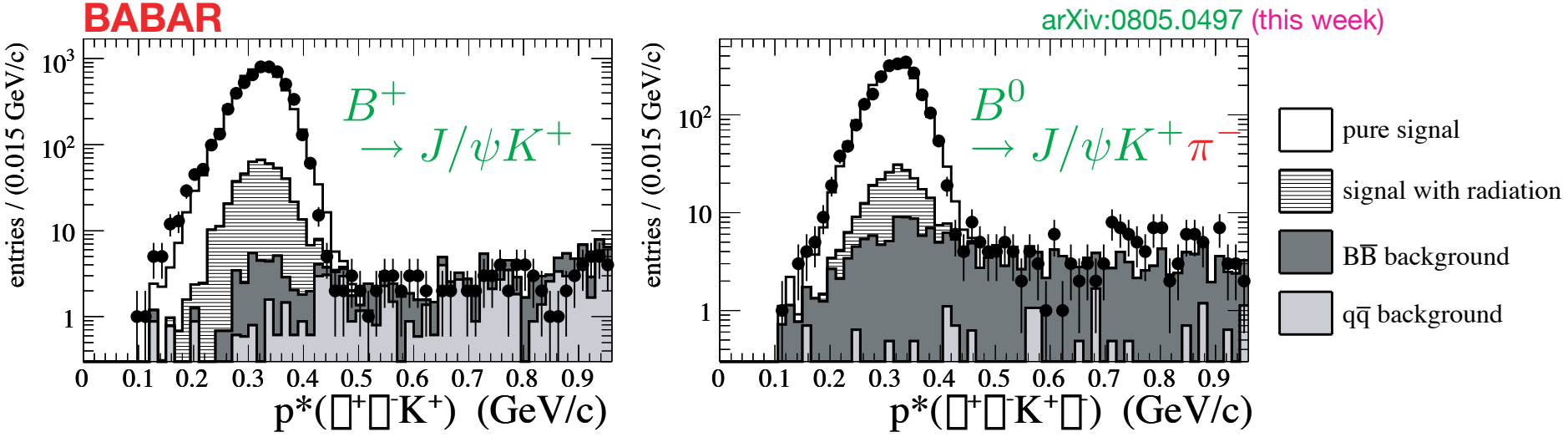
→ Complementary to $\Upsilon(4S)$ *B* factories



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

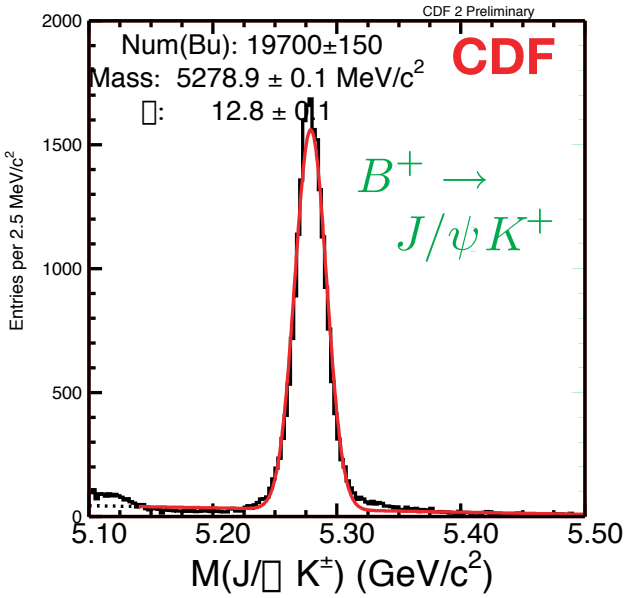
B_c Meson

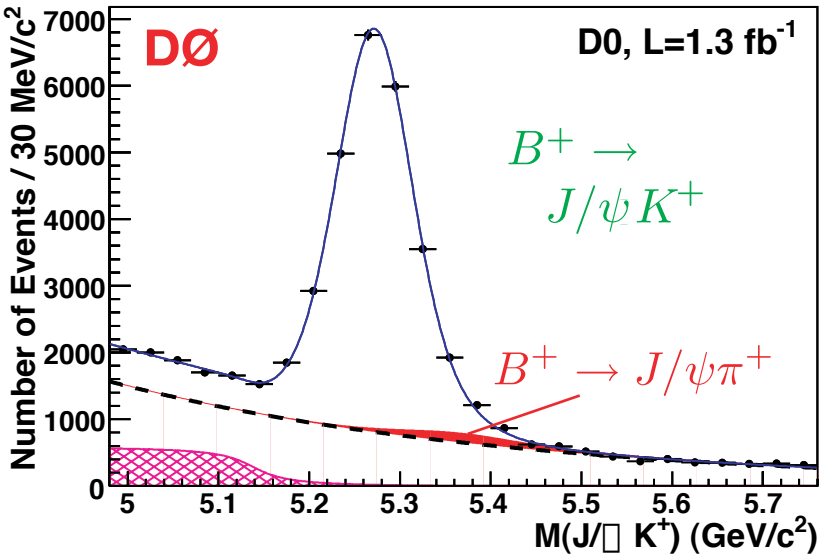
- Unique in that it contains two *different* heavy quarks
- Decays: via b quark $B_c^+ \to B_s^0\pi^+;\ B_s^0\ell^+\nu$
  via c quark $B_c^+ \to J/\psi\pi^+;\ J/\psi D_s^+;\ J/\psi\ell^+\nu$
  annihilation $B_c^+ \to \ell^+\nu$

first evidence, but poor mass measurement

- 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...

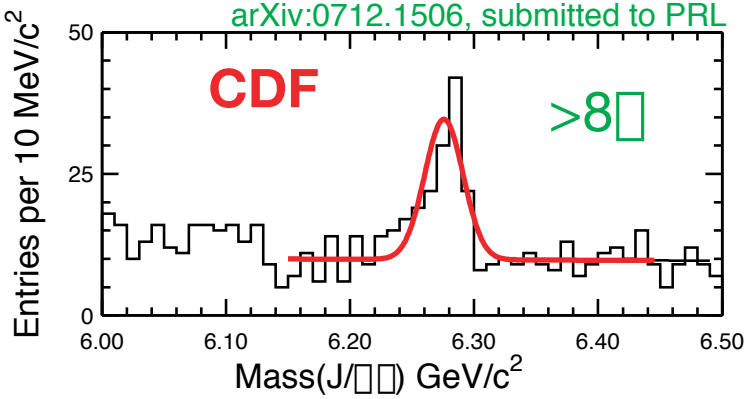
$\hookrightarrow \mu^+\mu^-$ – trigger, mass const.





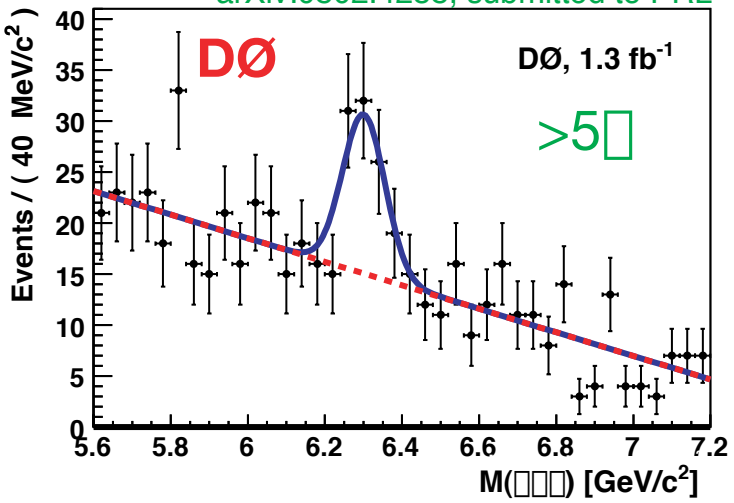
B_c Meson

arXiv:0712.1506, submitted to PRL



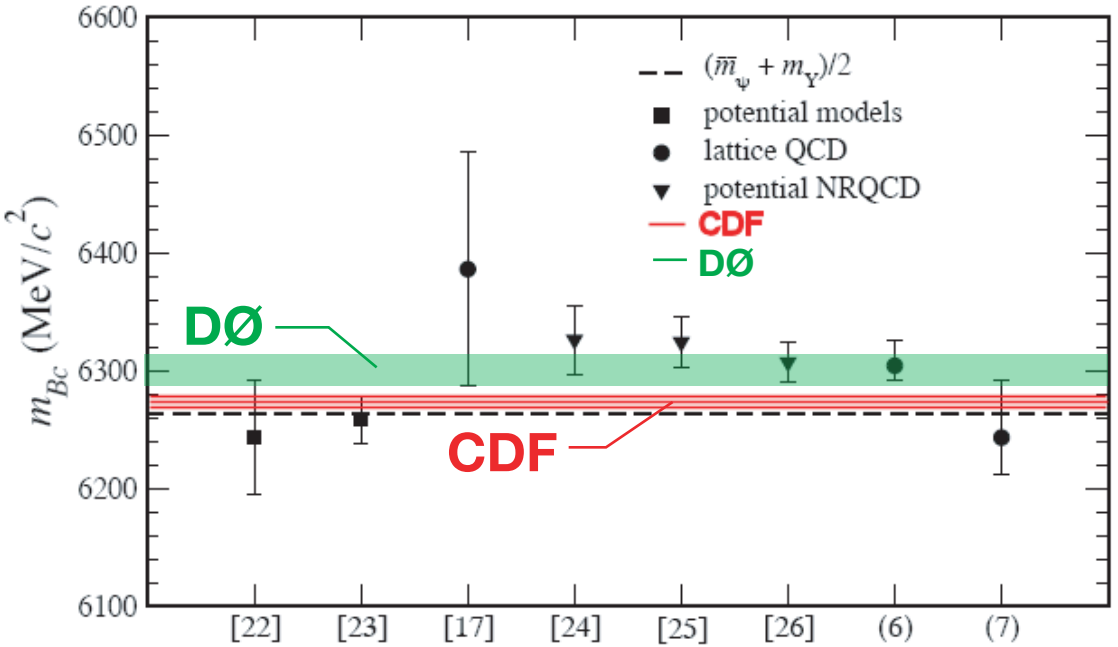
$$m(B_c^+) = 6275.6 \pm 2.9 \pm 2.5\,\mathrm{MeV}$$

arXiv:0802.4258, submitted to PRL



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

- Comparison to predictions:

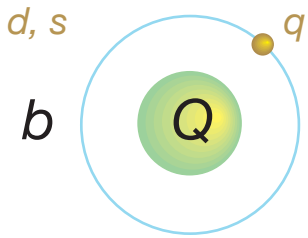


Different models →

- Experimental measurements now smaller undertainty than uncertainties on theoretical predictions

Spectroscopy

Hydrogen atom of strongly interacting systems



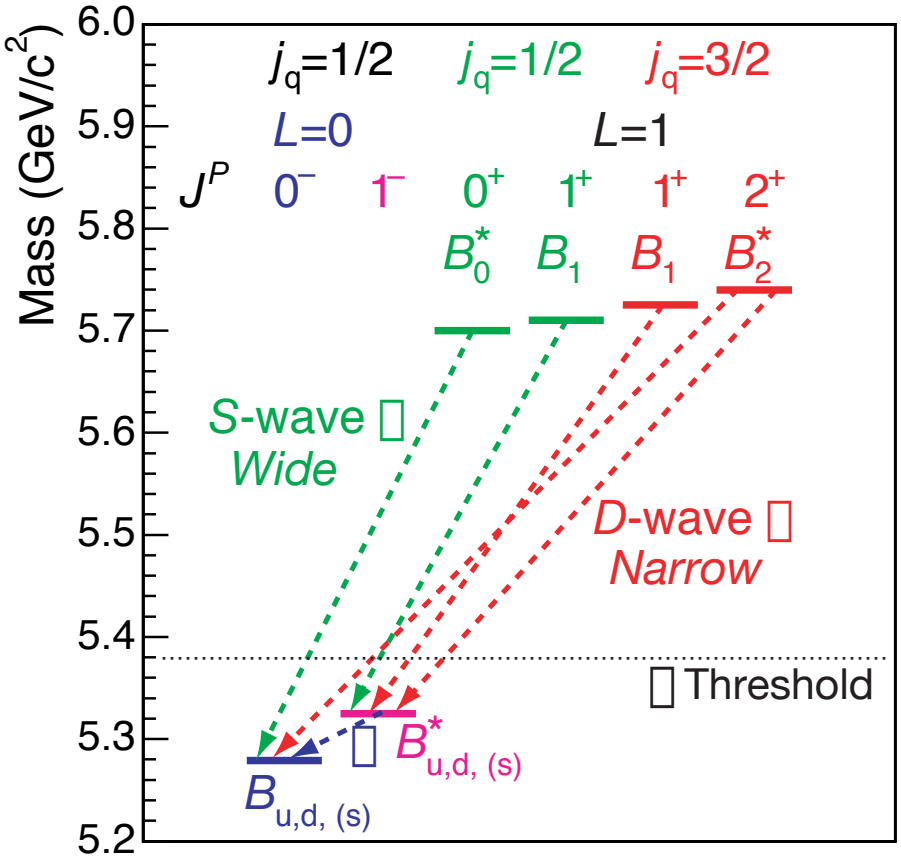
(+ gluon degrees of freedom, "brown muck")

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}



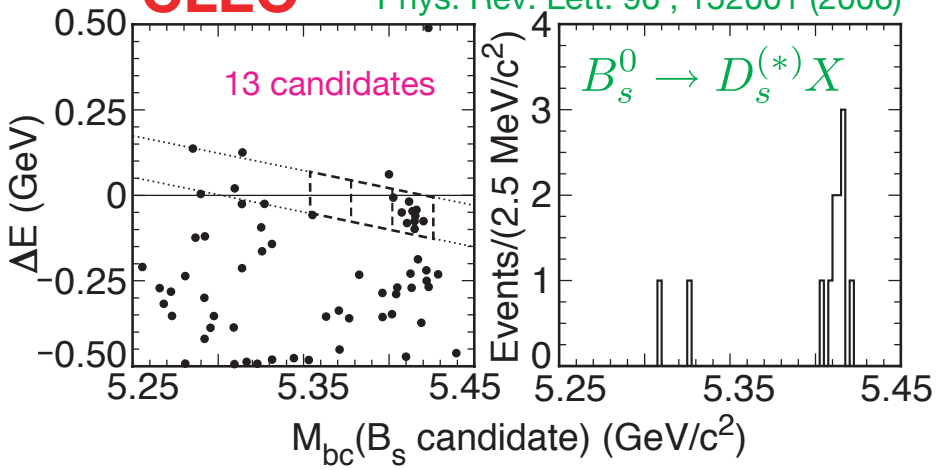
$B^0_{(s)1} \not\to B^+_{(s)}\pi^-$

forbidden by conservation of parity and angular momentum

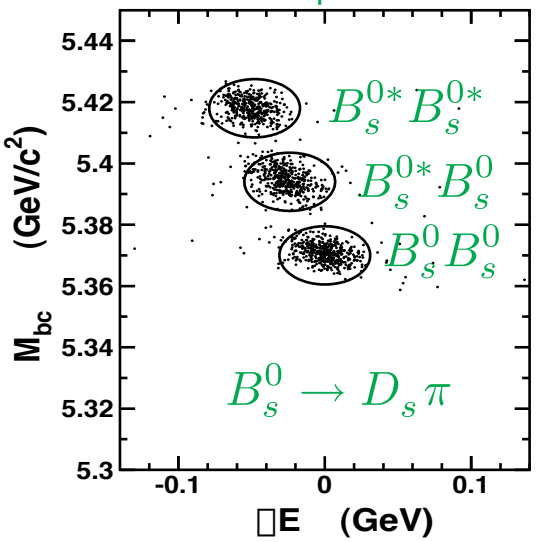
but first about that ...

B_s^* State

CLEO Phys. Rev. Lett. 96 , 152001 (2006)



Belle arXiv:hep-ex/0610003



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

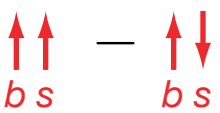
$$M(B_s^*) = 5411.7 \pm 1.6 \pm 0.6\,\mathrm{MeV}$$
$$\Delta M(B_s^* - B_s) = 45.7 \pm 1.7 \pm 0.7\,\mathrm{MeV}$$

- Similarly, **Belle**

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

1.8□ higher

- My average (including CUSB2 measurement)



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

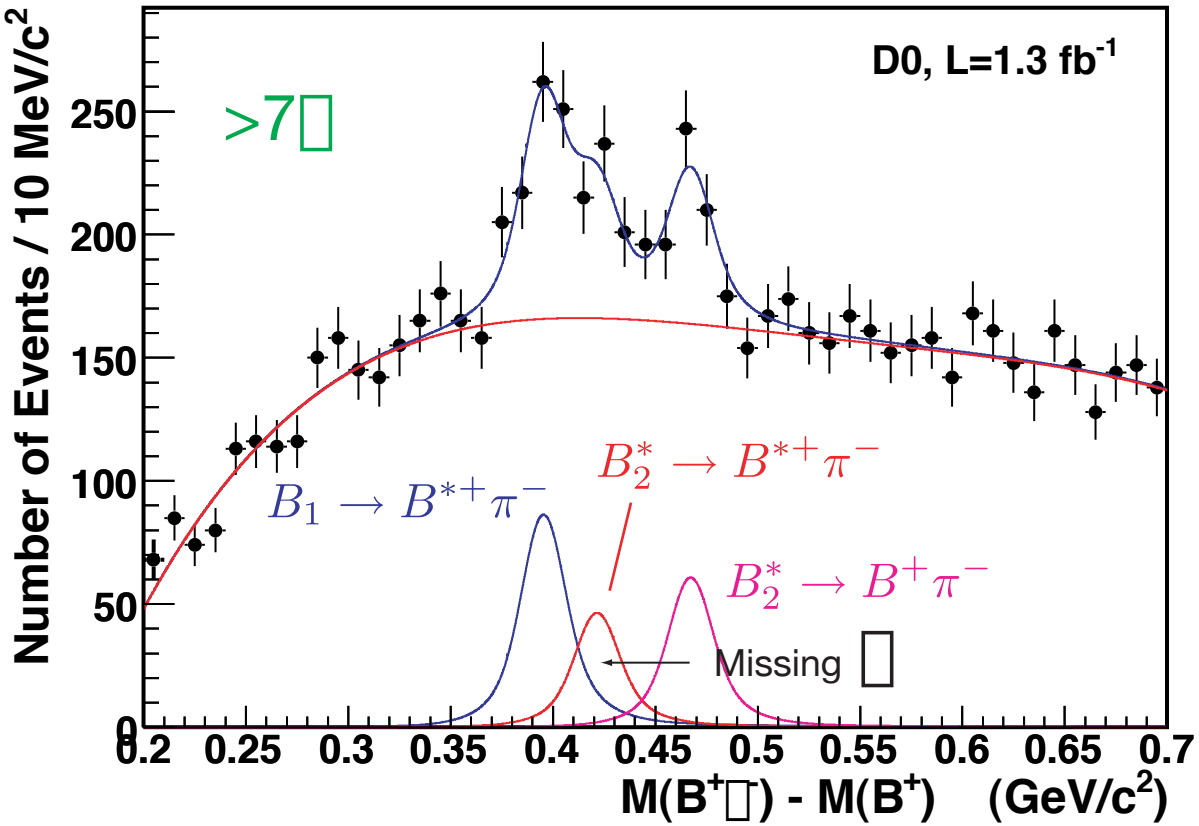
B^{**} States

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

Do not reconstruct

DØ

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

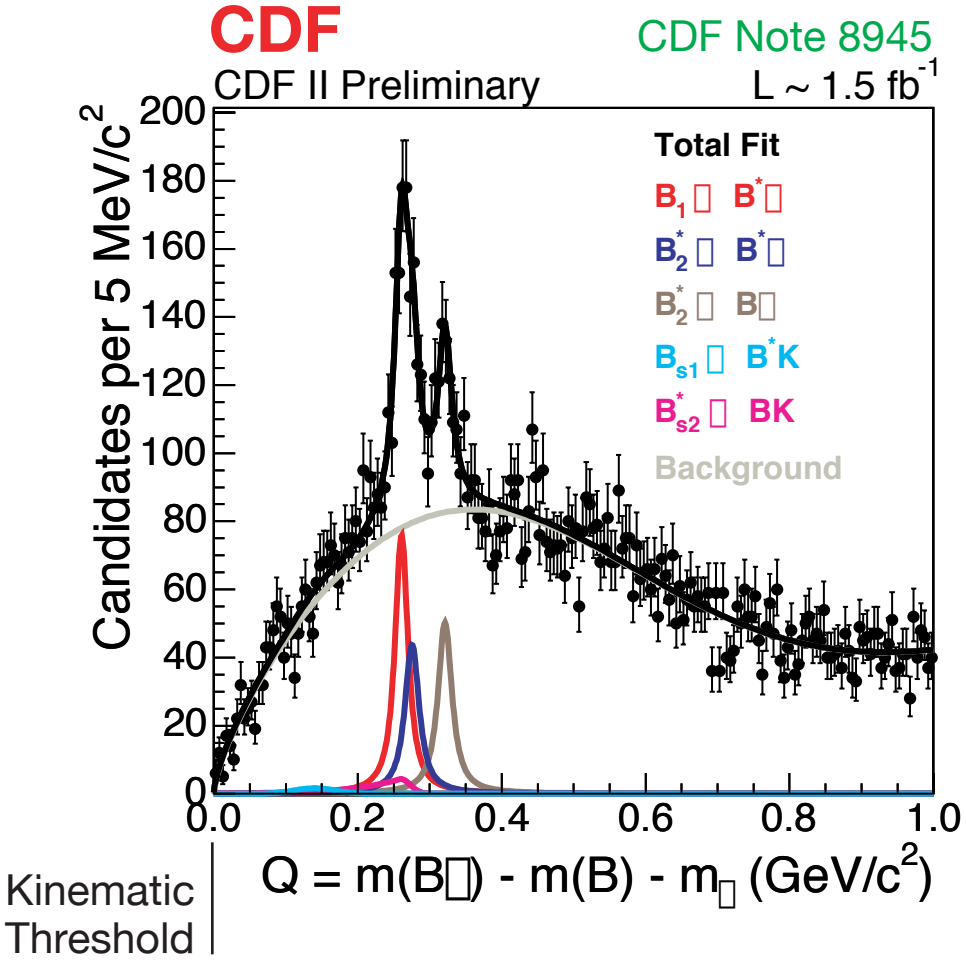


- Reconstruct $B^+ \to J/\psi K^+$ (~23k) then add a pion
- First time these states were separated

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

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)

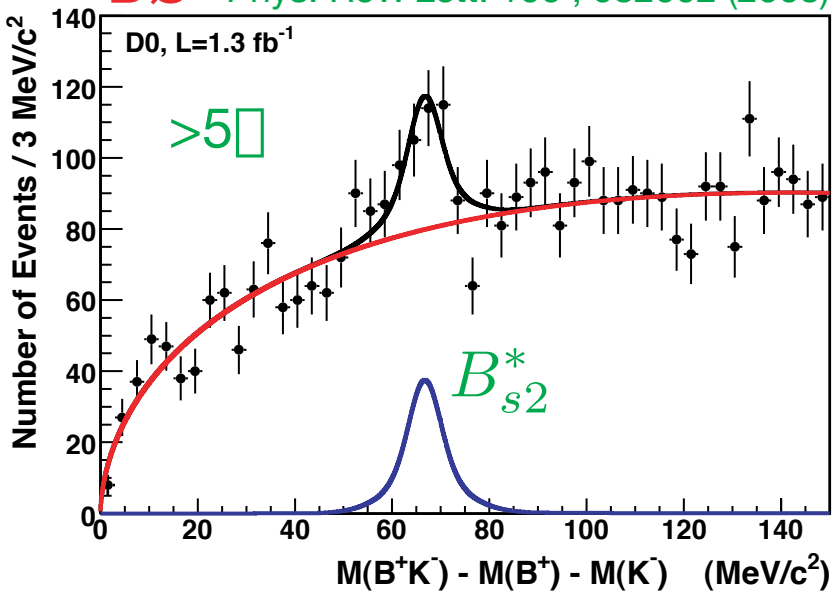
$$\Gamma(B_2^{*0}) = 22.1^{+3.6+3.5}_{-3.1-2.6}\,\mathrm{MeV}$$

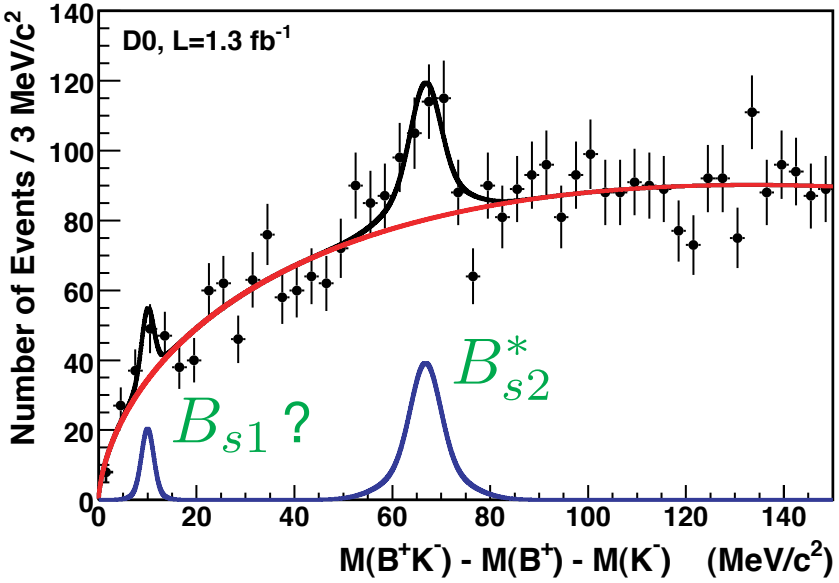
$$M(B_1^0) = 5725.3^{+1.6+0.8}_{-2.1-1.1}\,\mathrm{MeV}$$
$$M(B_2^{*0}) = 5739.9^{+1.7+0.5}_{-1.8-0.6}\,\mathrm{MeV}$$

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

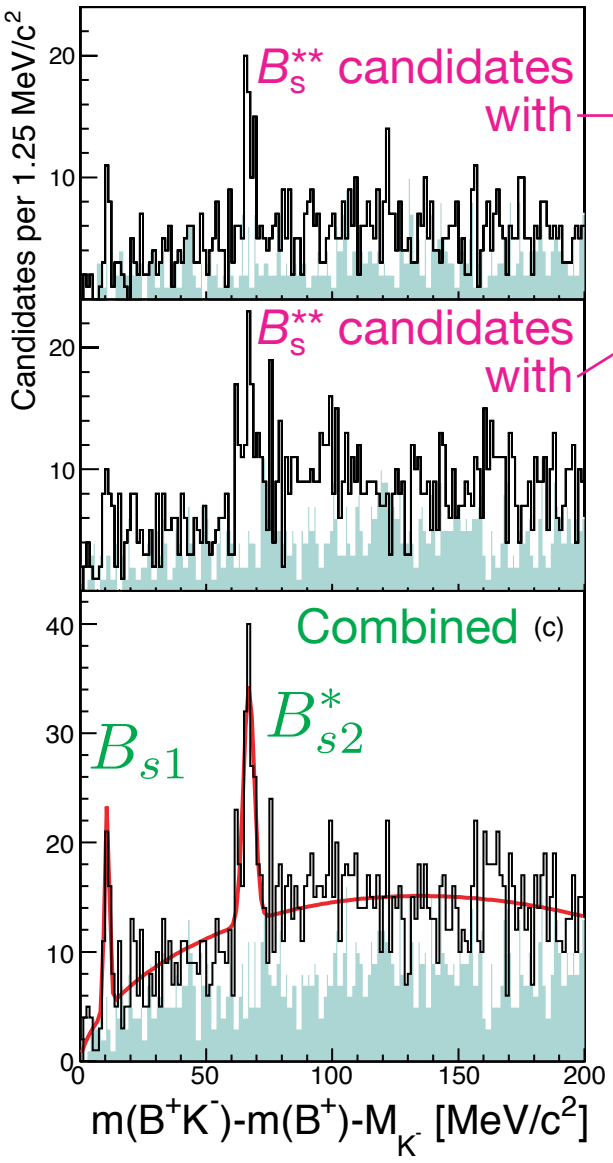
$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7\,\mathrm{MeV}$$

- 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

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

CDF arXiv:0710.4199



- 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)

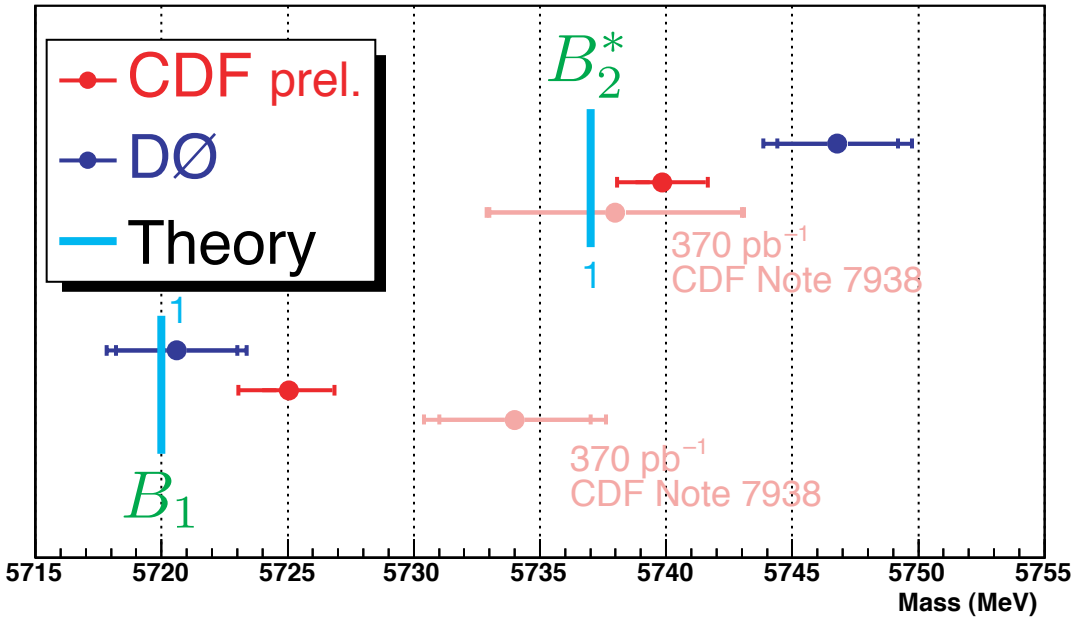
- First evidence of narrow B_{s1} state

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

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

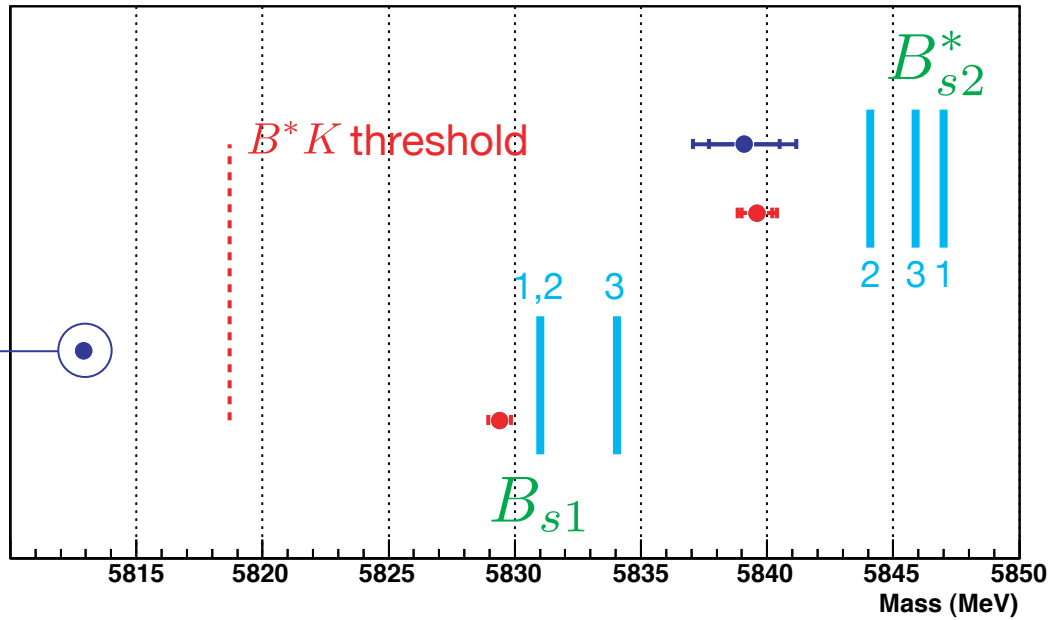
Theory: 1. Matsuki et al., hep-ph/0605019
2. Ebert et al., PRD 57, 5663;
3. Eichen et al., PRL 71, 4116

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

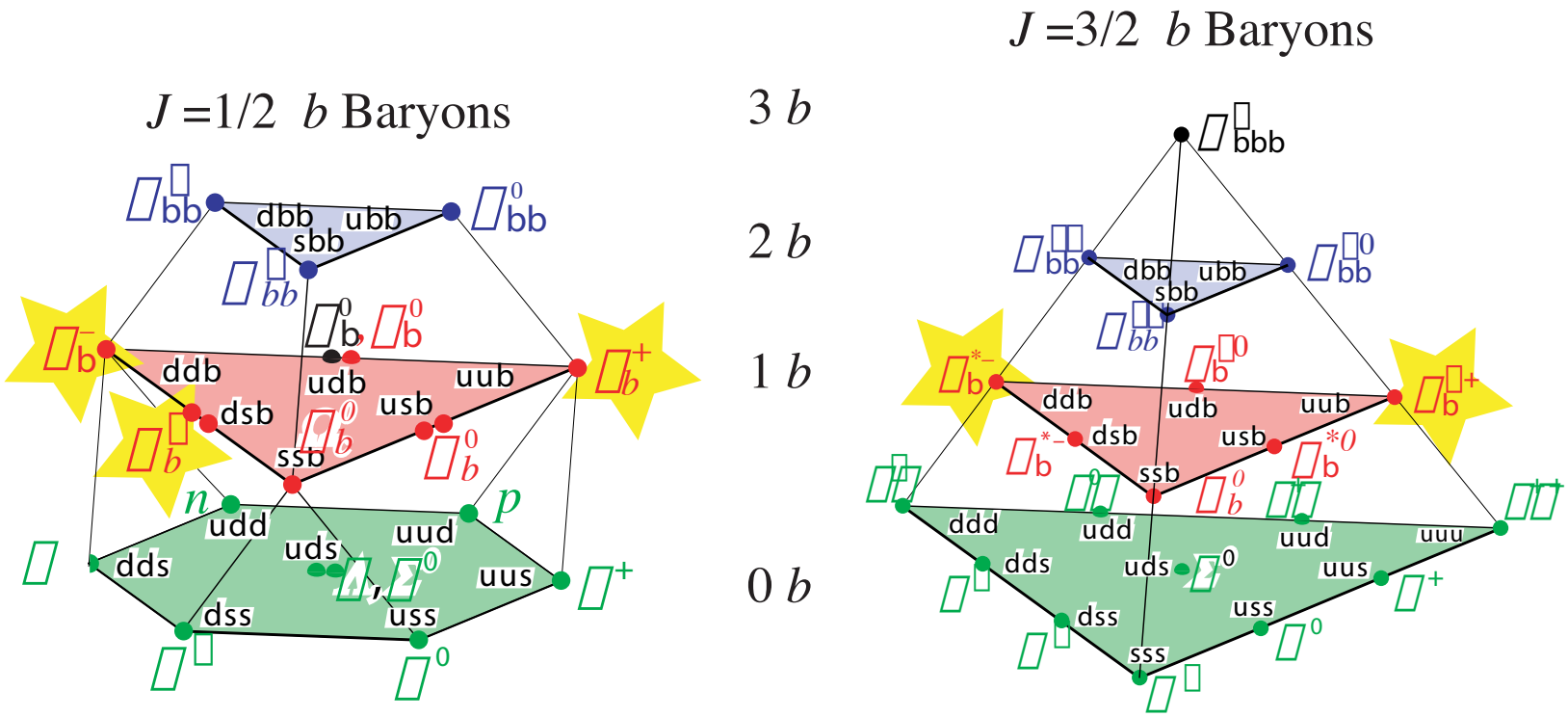


Phys. Rev. Lett. 100, 082002 (2008)
arXiv:0710.4199

Predicted from DØ $\Delta M(B^{**})$



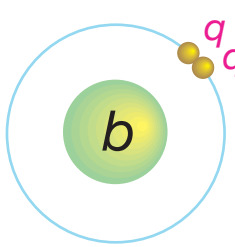
New *b*-Flavored Baryons



- 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*



spin-0: Λ_b
spin-1: Σ_b

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

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

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

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

Σ_b: *bqq*

$$J^P = S_Q + s_{qq}$$
$$= 3/2^+: \ \Sigma_b^*$$
$$= 1/2^+: \ \Sigma_b$$

- 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.) $m(\Sigma_b^-) - m(\Sigma_b^+)$	$5 - 7$
$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim 8, \sim 15$

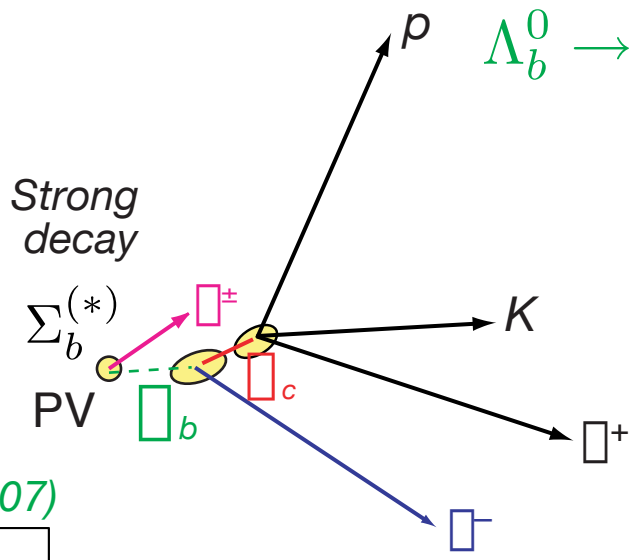
Λ_b Heavy Baryon

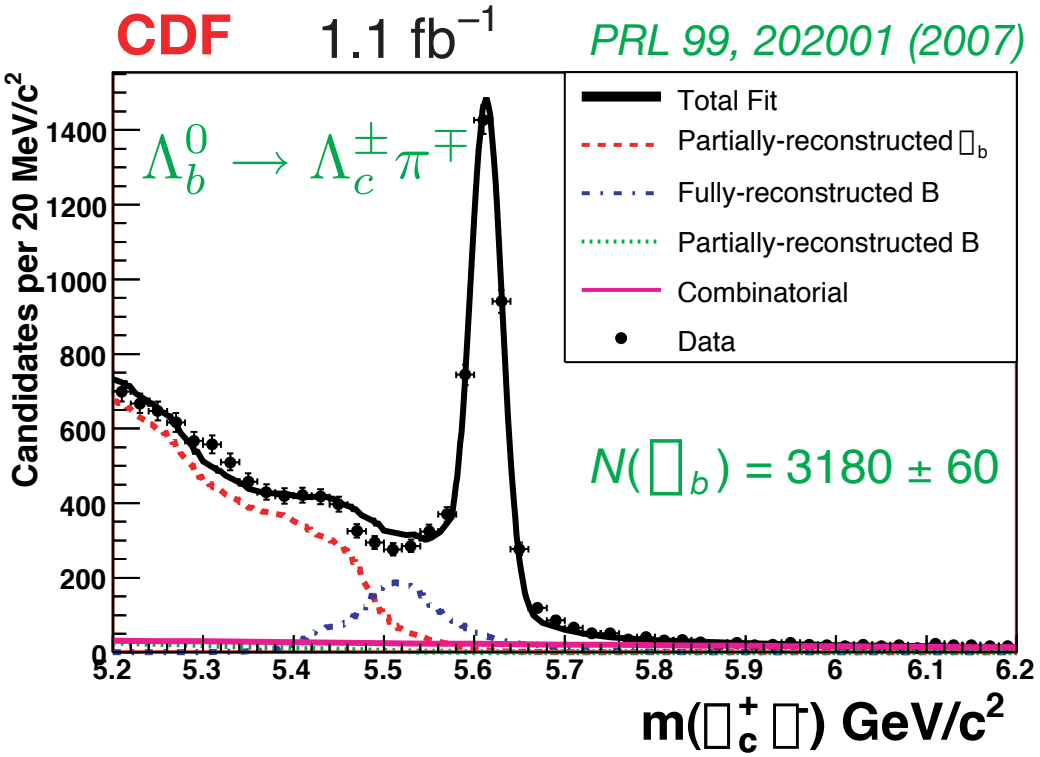
$\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm;$

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

$\Lambda_c \to pK\pi$

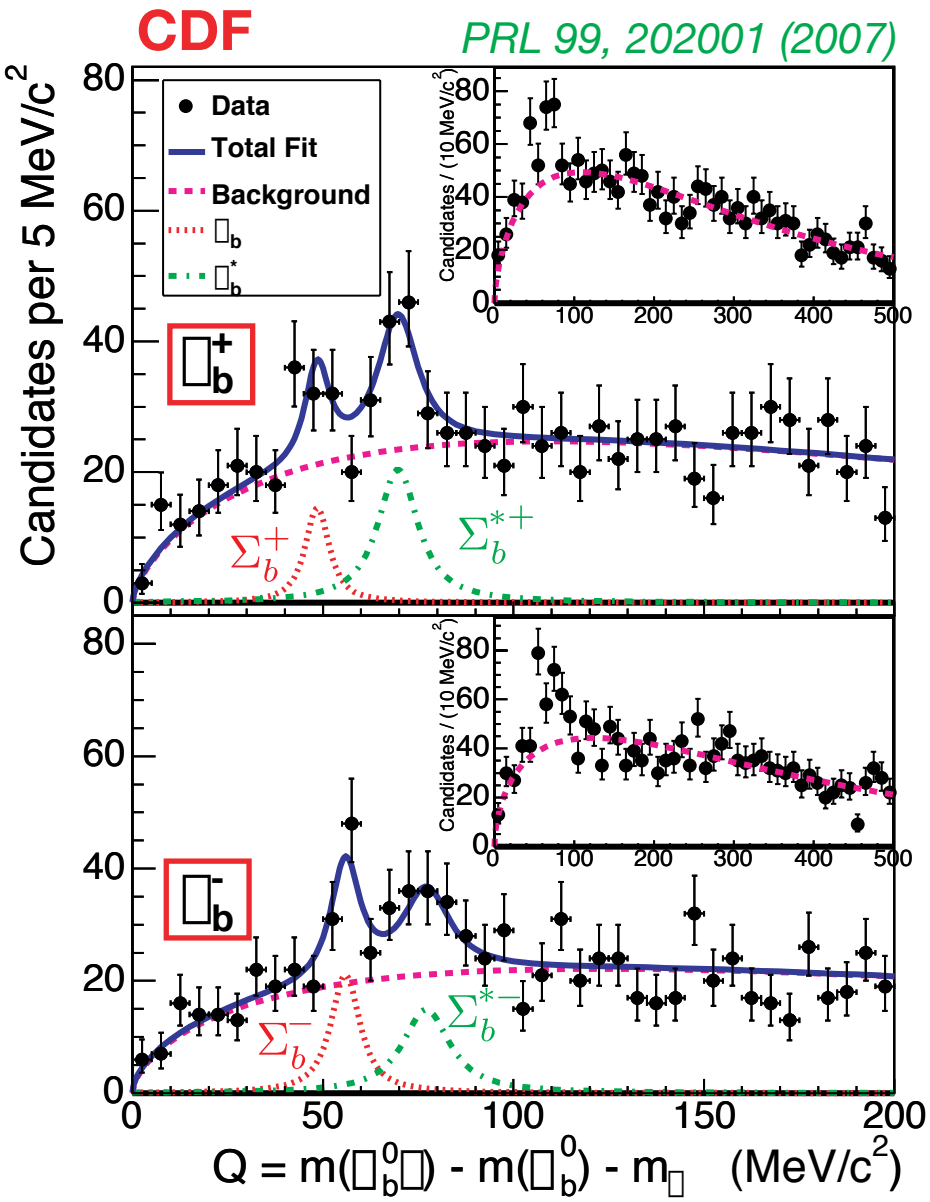
- Form a large optimized sample of $\Lambda_b^0 \to \Lambda_c^\pm \pi^\mp$





- 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

□b Heavy Baryon



- Constrain $m(\Sigma_b^{*+}) - m(\Sigma_b^{+}) = m(\Sigma_b^{*-}) - m(\Sigma_b^{-})$
- Two peaks for each charge, 5.2□ 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:

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

Λb 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.*

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	$195.5 \pm 1.0 \pm 0.2$ *
(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"

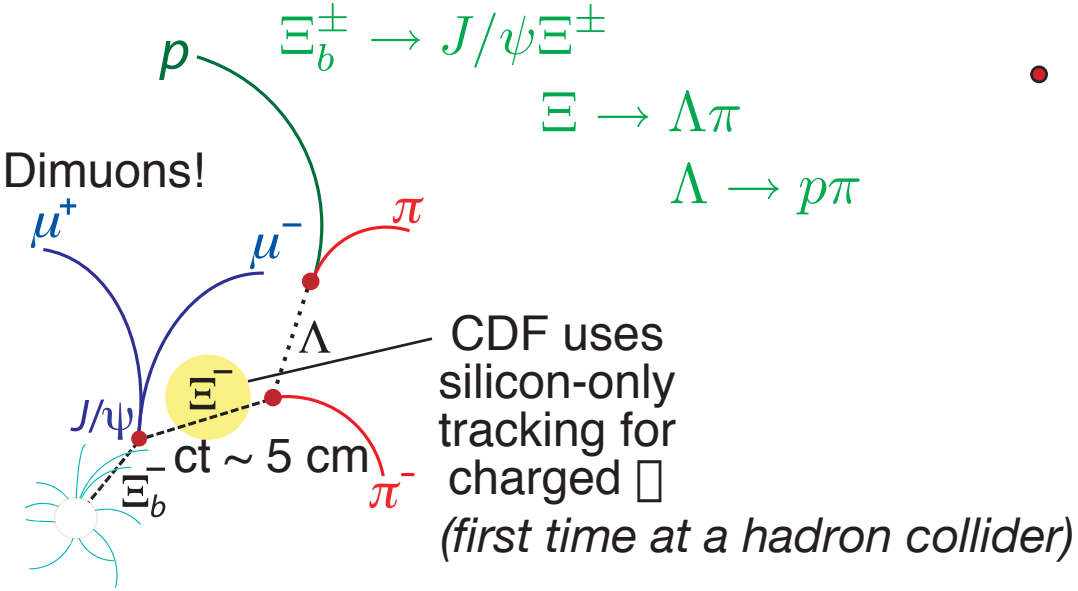
- Quark content: Ξ_b^0 : *bsu* (struck through) $\quad \Xi_b^- : bsd$

$\Xi_b^0 \to \Xi_c^0 \pi^0$ $\qquad$ $\Xi_b^0 \to D^0 \Lambda$

$\Xi_b^\pm \to J/\psi \Xi^\pm$ $\qquad$ $\Xi_b^\pm \to \Xi_c^0 \pi^\pm$

CDF, DØ $\qquad$ CDF

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



CDF uses silicon-only tracking for charged Ξ

(first time at a hadron collider)

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

Ξb Heavy Baryon

"Strangely Beautiful Baryon"
"Triple Scoop Baryon"

- Quark content: Ξ_b^0 : *bsu* ~~(struck through)~~
  Ξ_b^- : *bsd*

$\Xi_b^0 \to \Xi_c^0 \pi^0$ $\quad$ $\Xi_b^0 \to D^0 \Lambda$

$\Xi_b^\pm \to J/\psi \Xi^\pm$ $\quad$ $\Xi_b^\pm \to \Xi_c^0 \pi^\pm$

CDF, DØ $\quad$ CDF

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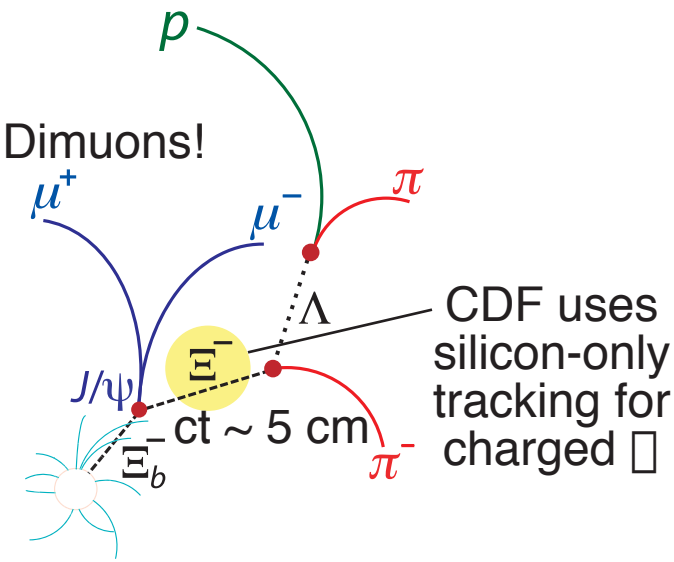
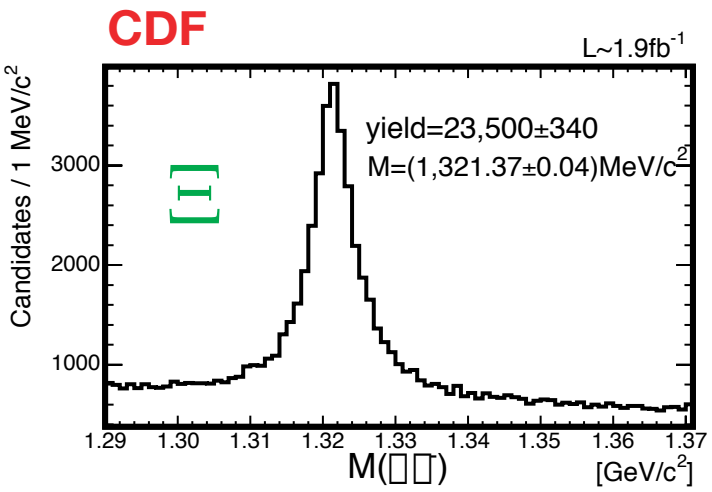
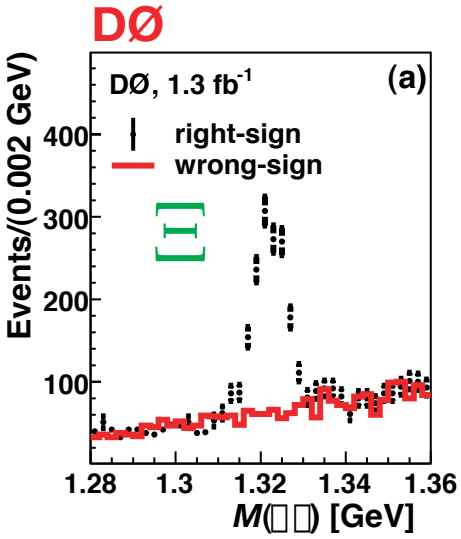




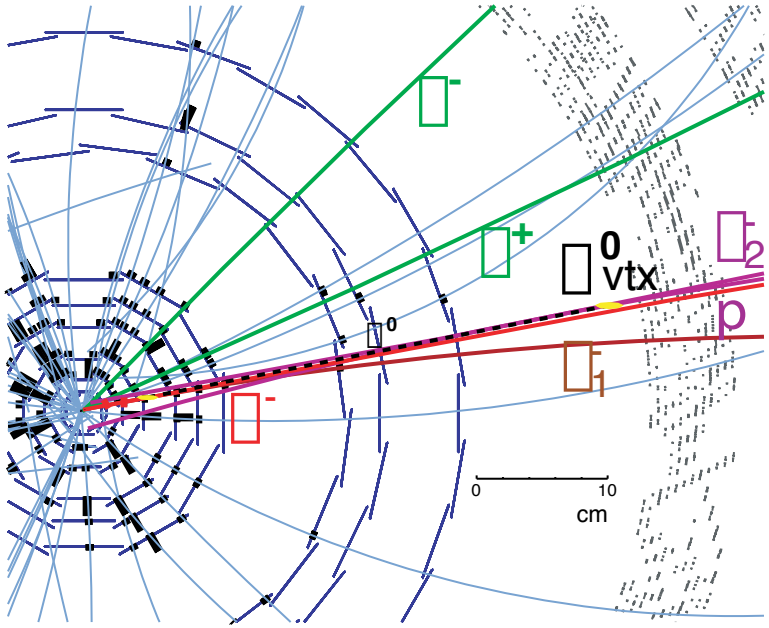


Λ_b Heavy Baryon

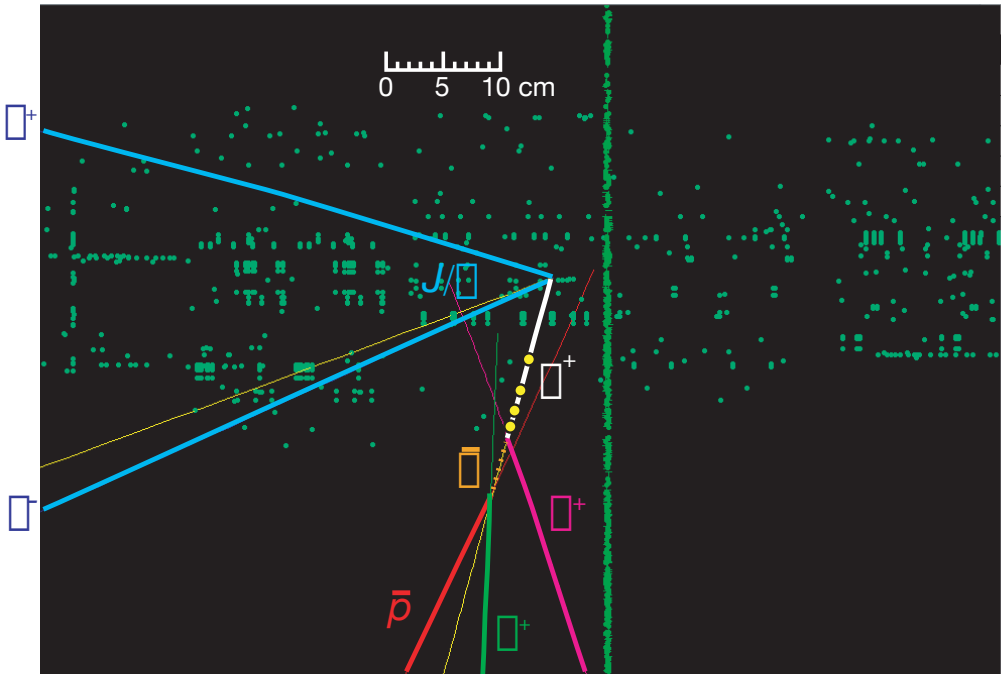
"Strangely Beautiful Baryon"
"Triple Scoop Baryon"

- 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



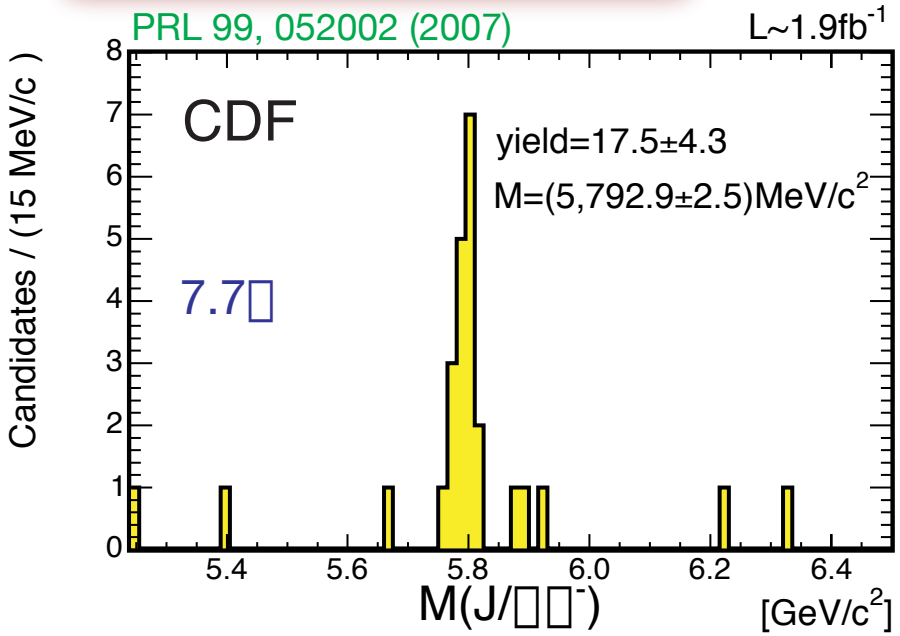
DØ



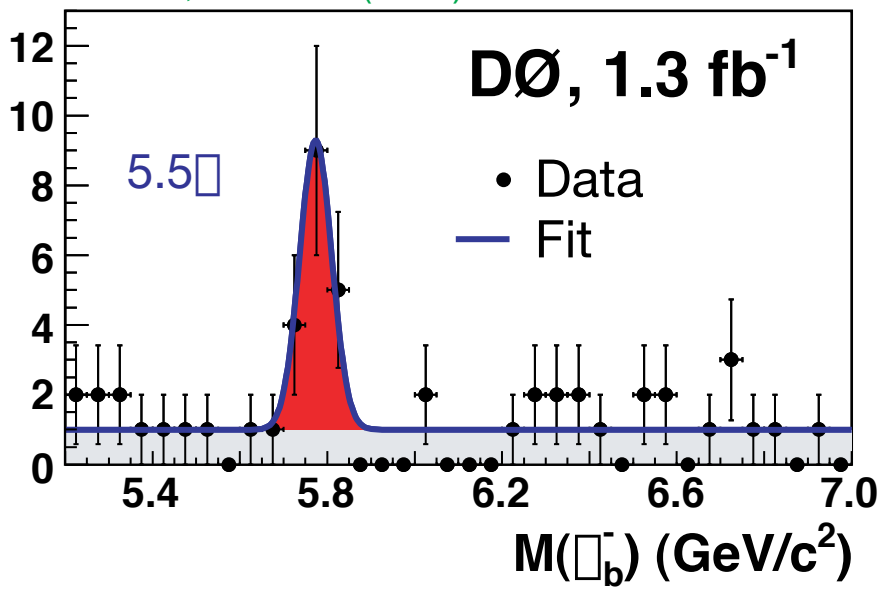
Run 179200, Event 55278820, $M(\Lambda_b)$ = 5.788 GeV

□b Heavy Baryon

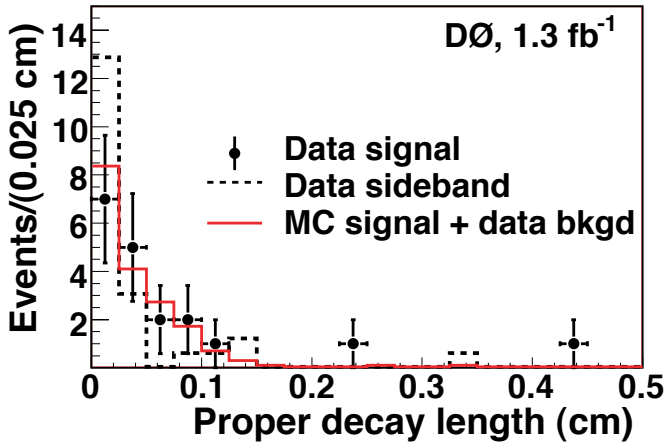
PRL 99, 052002 (2007)



PRL 99, 1052001 (2007)



- 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:



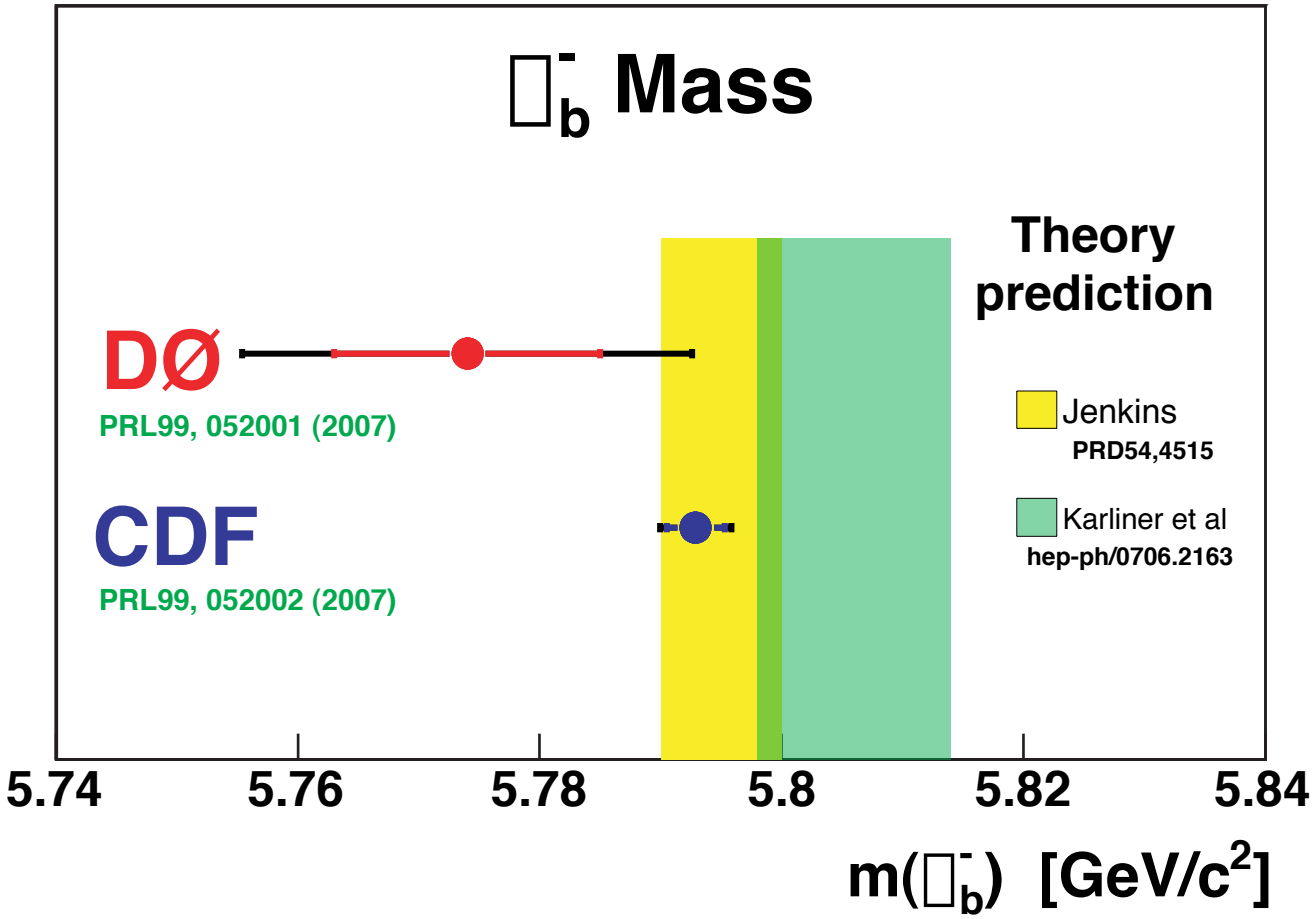
CDF

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

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^{**} 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...?*)?