Baryon Spectroscopy

April 27, 2010

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CDF Collaboration

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Outline

- How do CDF/D0 go about observing baryons
- The observation of the Ω_b^- and the Ξ_b^-
  - A review of the CDF/D0 disagreement
- Measurements of the Λ_b^0 lifetime
  - Semileptonic decays, hadronic decays, and decays to J/ψ final states
- Charm resonances in $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$
- SELEX observation of doubly charmed baryons
- Mass measurement of excited charmed baryons

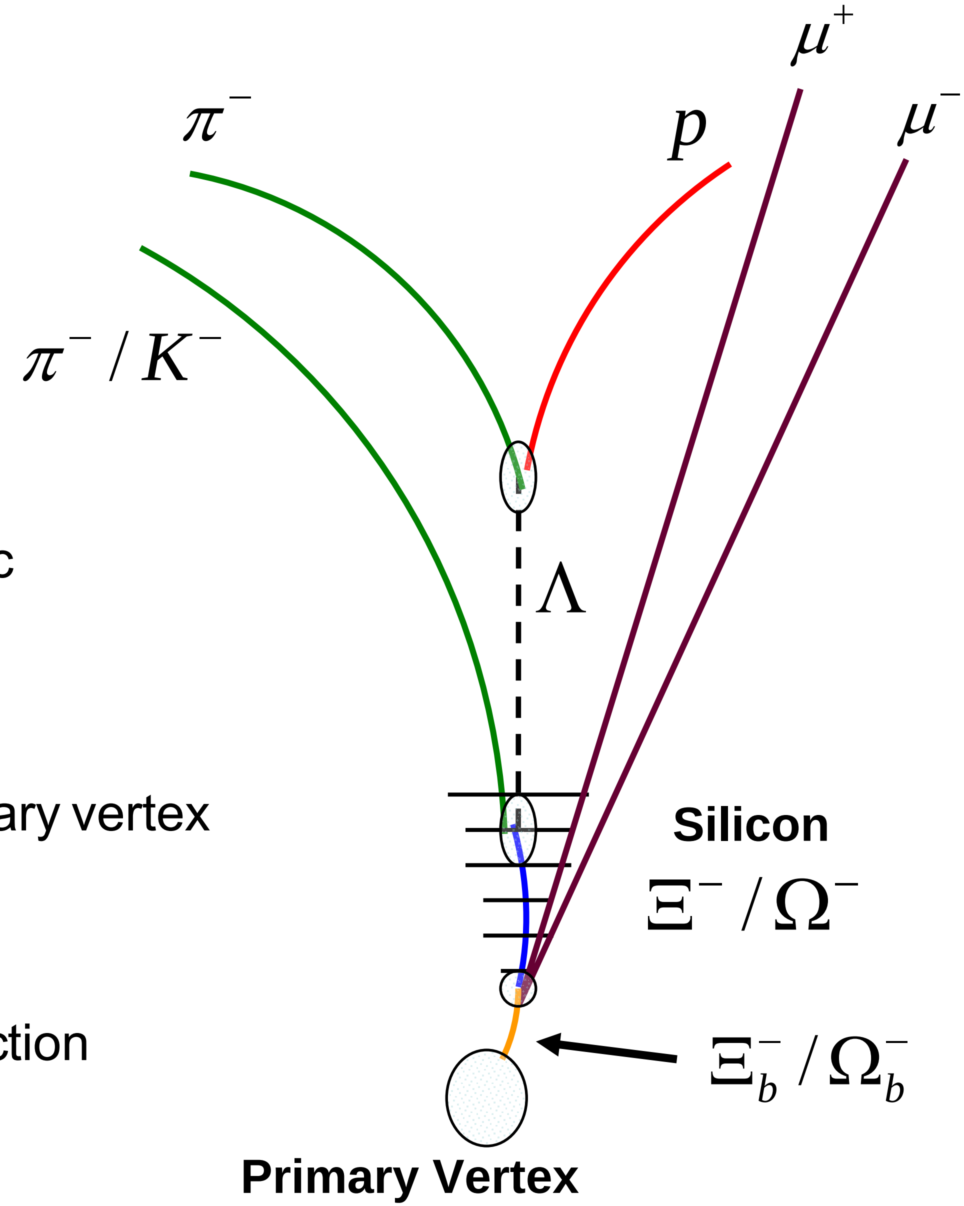
How to go about observing heavy baryons, from the CDF/D0 perspective

Triggers for baryons

- Single muon (CDF and D0) $\rightarrow$ semileptonic decays
- Dimuon (CDF and D0) $\rightarrow$ decays to $(J/)\psi X$
- Displaced tracks (CDF) $\rightarrow$ hadronic and semileptonic decays

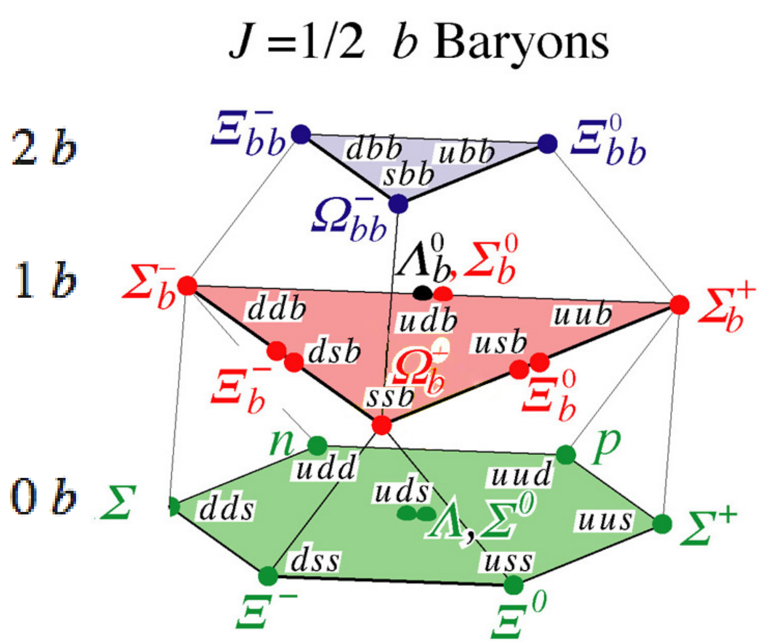
Reconstructing baryons

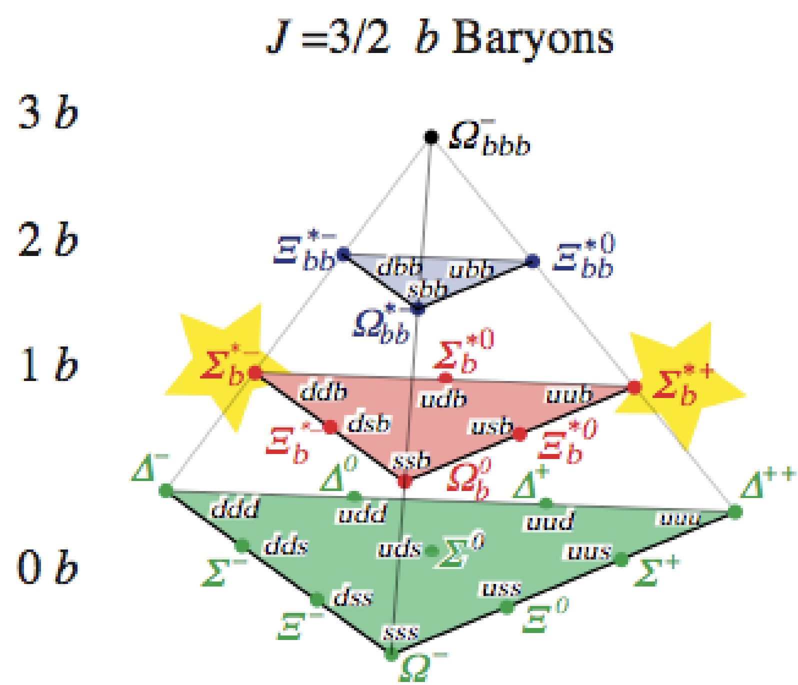
- Good charged particle and secondary vertex reconstruction in tracker
- PID in muon chambers, dE/dx, ToF
- No neutron and neutrino reconstruction (at low p_T)



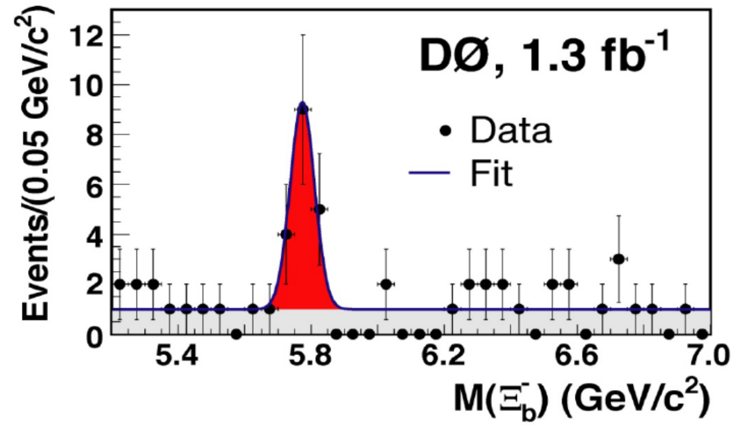
Our knowledge of the bottom baryons has greatly increased over the past few years

- CDF and D0 have dominated the field
- $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$ discovered in 2006 (CDF : PRL 99,202001(2007))
- Ξ_b^- discovered in 2007 (D0 : PRL 99,052001(2007))
- Ω_b^- discovered in 2008 (D0 : PRL 101,232002(2008))





The CDF and D0 observations of the Ξ_b^- are in good agreement



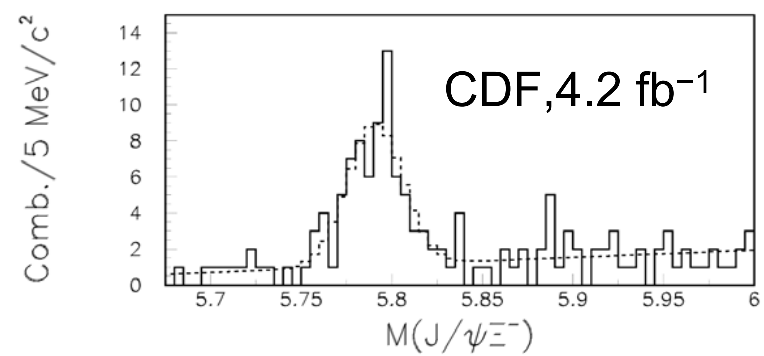
For the mass measurement

CDF, $m(\Xi_b^-) = 5790.9 \pm 2.6\,(\text{stat.}) \pm 0.8\,(\text{syst.})\ \mathrm{MeV/c^2}$

D0, $m(\Xi_b^-) = 5744 \pm 11\,(\text{stat.}) \pm 15\,(\text{syst.})\ \mathrm{MeV/c^2}$

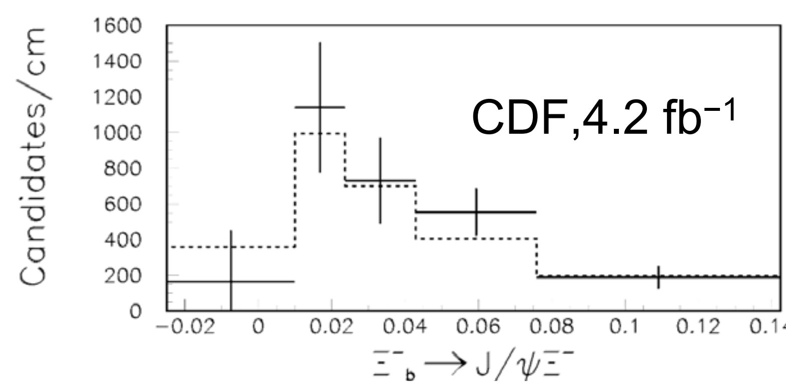
CDF then makes the additional measurement of the lifetime

$\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25}(\text{stat.}) \pm 0.02(\text{syst.})\ \mathrm{ps}$



Lifetime measurement is statistically limited

- Ξ_b^- signal yield was only 61
- 17% relative lifetime error
- Doubling data (8 - 10 fb^{-1}) would yield 10% precision



D0 : Phys. Rev. Lett. 99, 052001(2007)

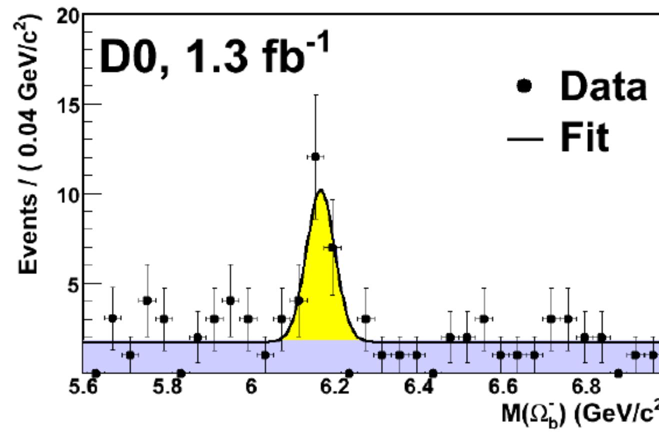
CDF : Phys. Rev. D80, 072003 (2009)

The CDF and D0 measurements of the Ω_b^- mass appear inconsistent

For the mass measurement

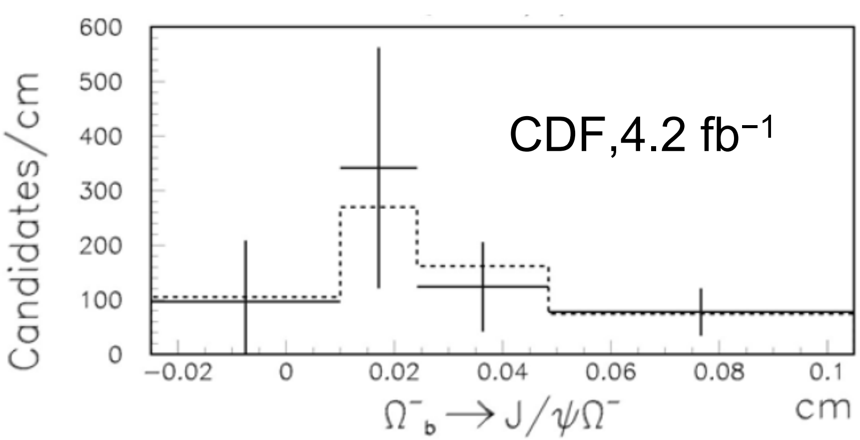
CDF, $m(\Omega_b^-) = 6054.4 \pm 6.8\,(\text{stat.}) \pm 0.9\,(\text{syst.})\ \mathrm{MeV/c^2}$

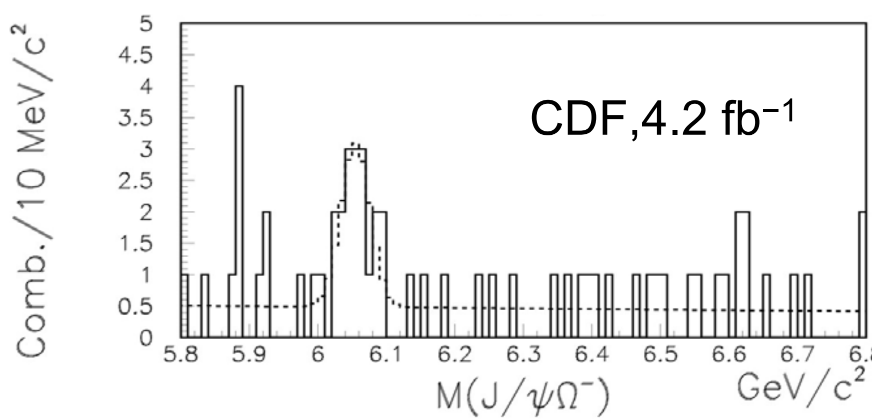
D0, $m(\Omega_b^-) = 6165 \pm 10\,(\text{stat.}) \pm 13\,(\text{syst.})\ \mathrm{MeV/c^2}$



CDF then makes the additional measurement of the lifetime

$\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40}(\text{stat.}) \pm 0.02(\text{syst.})\ \mathrm{ps}$



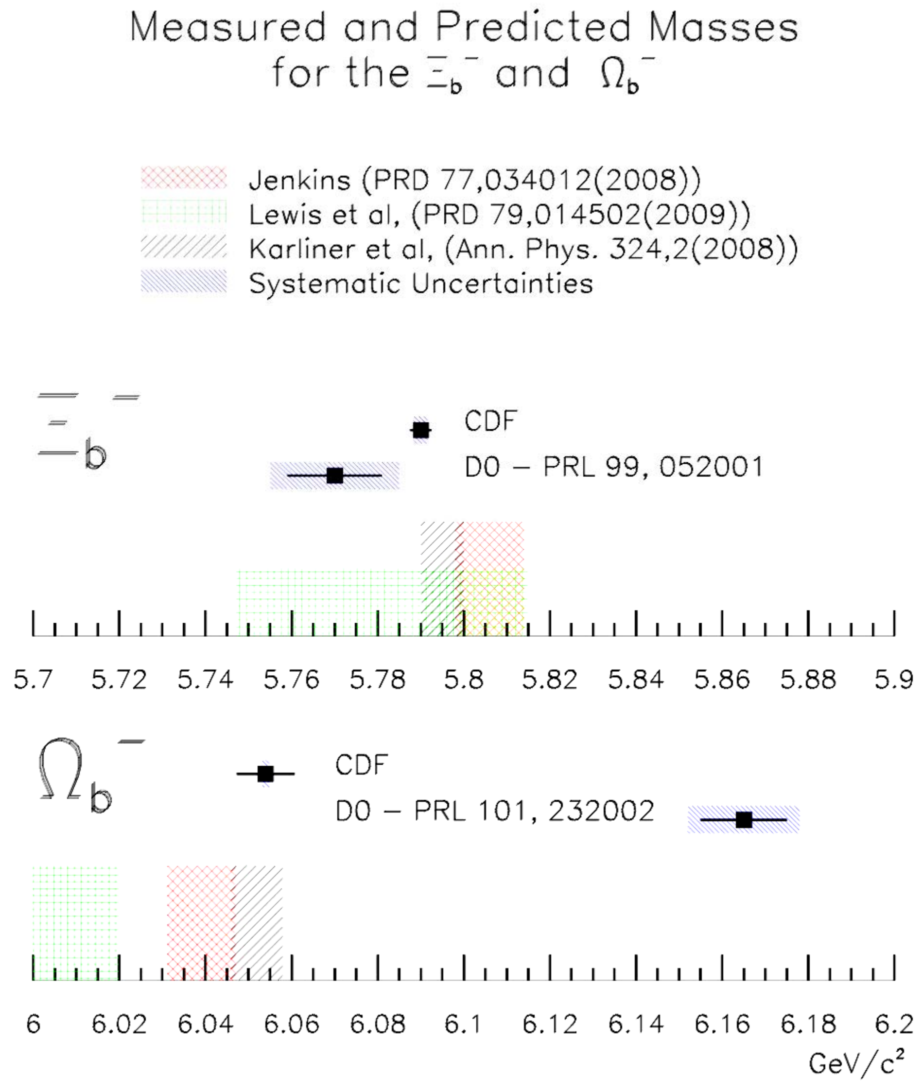


D0 : Phys. Rev. Lett. 101, 232002 (2008)

CDF : Phys. Rev. D80, 072003 (2009)

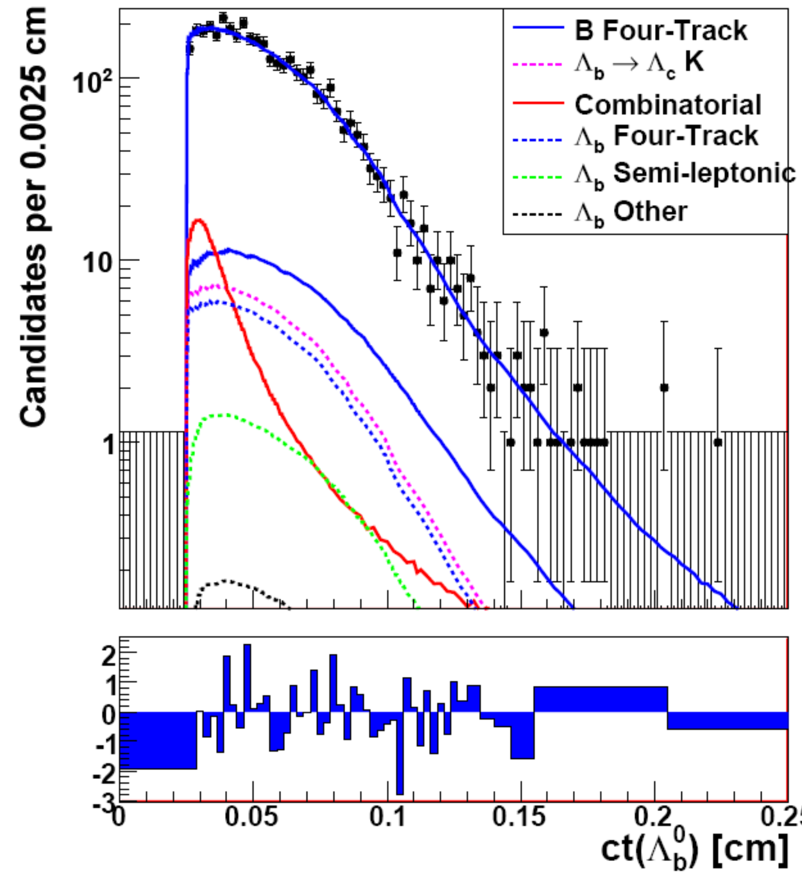
Comparing the CDF and D0 results to theory for the Ω_b^-

- Current estimates place $m(\Omega_b^-)$ in the range of $6010 - 6070\ \mathrm{MeV/c^2}$
- CDF measurement in the range, D0 differs by $\sim 6\sigma$
- D0 is in the process of including more data, will take some time
- Further analyses will hopefully shed light on the phenomenon



CDF has measured the Λ_b^0 lifetime in $\Lambda_b^0 \to \Lambda_c^+ \pi^- \to (pK^- \pi^+)\pi^-$

- Used 1.1 fb^{-1} of data off of the hadronic trigger
- Corrections applied to lifetime to account for displaced trigger
- Sequential unbinned likelihood fit performed over mass, then lifetime and lifetime error
- Yield of 2927 ± 58 candidates fit for $\Lambda_b^0 \to \Lambda_c^+ \pi^-$



CDF then measures

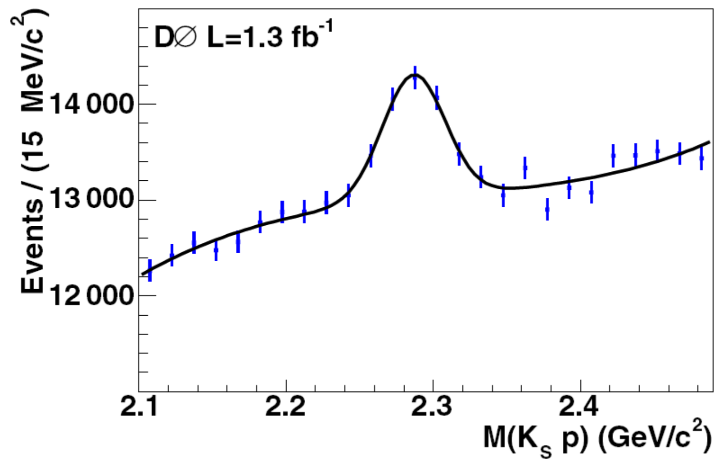
$$\tau(\Lambda_b^0) = 1.401 \pm 0.046(\text{stat.}) \pm 0.035(\text{syst.})\ \text{ps}$$

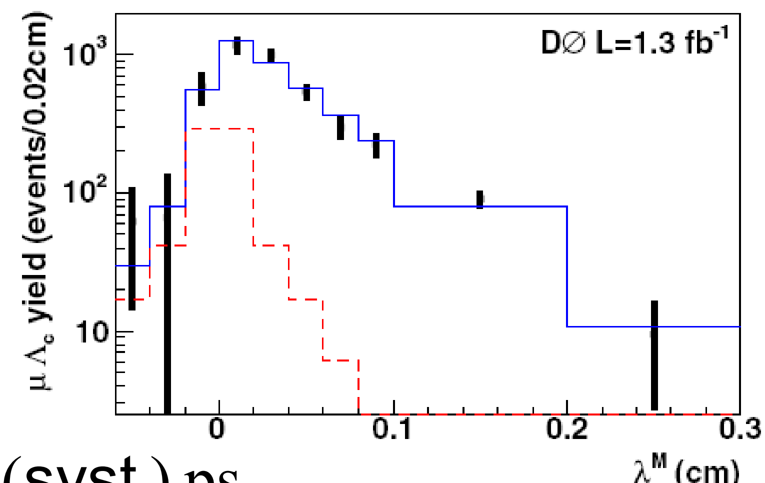
$$\tau(\Lambda_b^0)/\tau(B^0) = 0.916 \pm 0.038$$

CDF : Phys. Rev. Lett. 104, 102002 (2010)

The D0 collaboration has made a measurement of the Λ_b^0 lifetime using semileptonic decays

- Made use of the decay $\Lambda_b^0 \to \mu\bar{\nu}\Lambda_c^+ X$
- Events came off of the single muon trigger for 1.3 fb^{-1} for a yield of 4437 ± 329
- Correction for missing momentum (k - factor)





D0 then measures

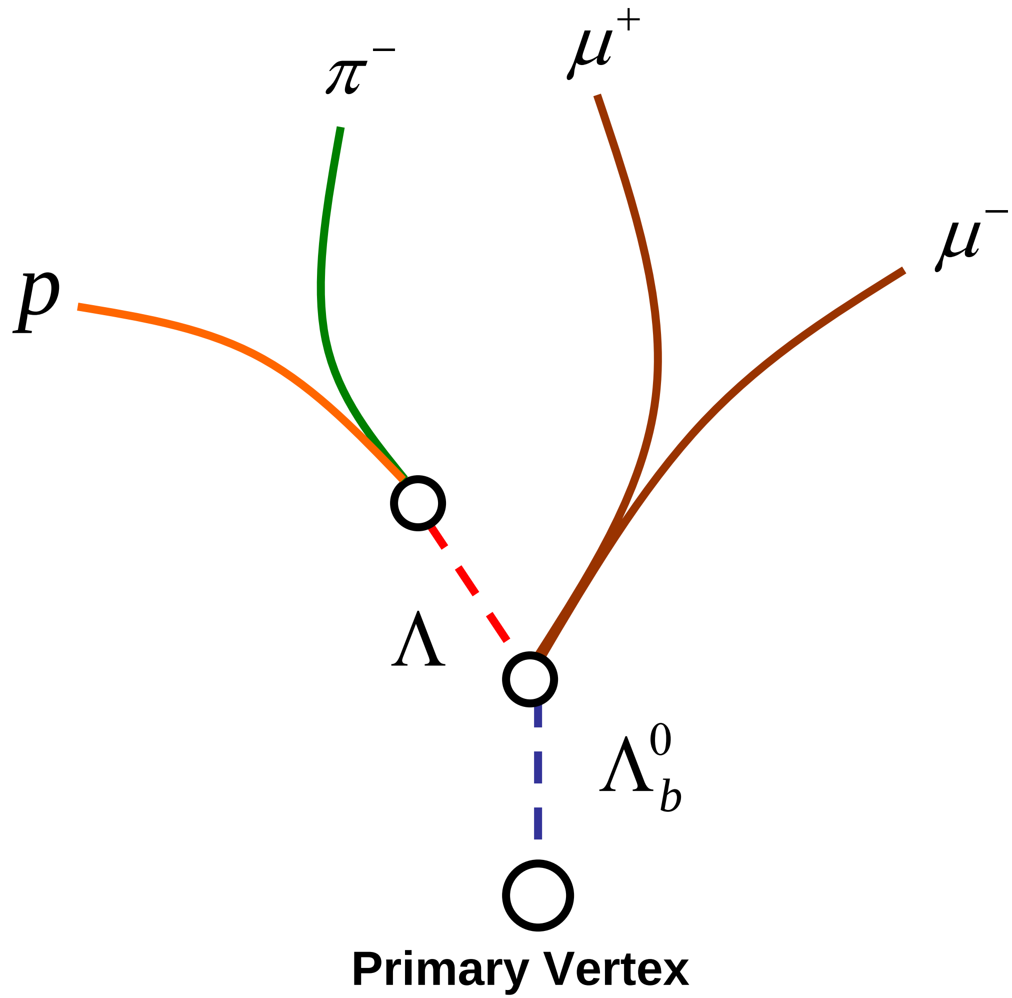
$$\tau(\Lambda_b^0) = 1.290\ ^{+0.119}_{-0.110}(\text{stat.})\ ^{+0.087}_{-0.091}(\text{syst.})\ \text{ps}$$

The value is in good agreement with other semileptonic measurements, the world average, and theory

D0 : Phys. Rev. Lett. 99, 182001(2007)

CDF has recently updated a measurement of $b-$hadron decays to J/ψ final states in 4.3 fb^{-1}

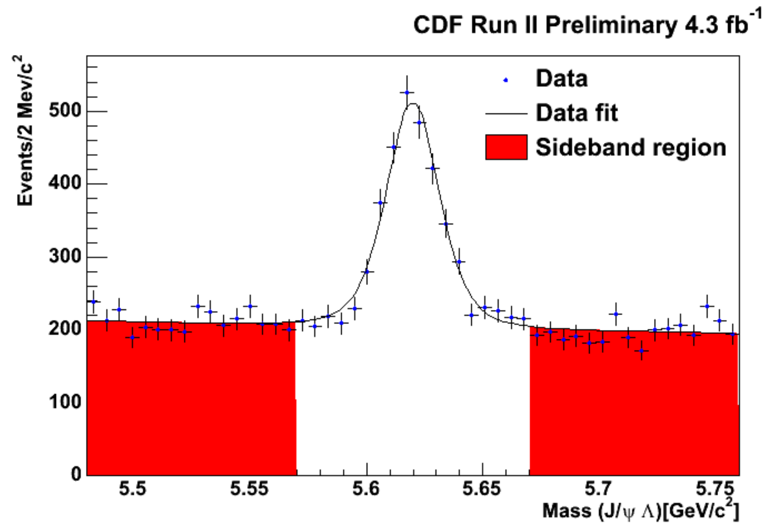
- Of interest here is the lifetime ratio $\tau(\Lambda_b^0)/\tau(B^0)$
- Events taken off of the dimuon trigger for $J/\psi \to \mu^+\mu^-$
- Measure ct from the J/ψ vertex, therefore insensitve to details of Λ reconstruction and kinematics
- Yield of 1710 ± 50 $\Lambda_b^0 \to J/\psi\Lambda^0$ found



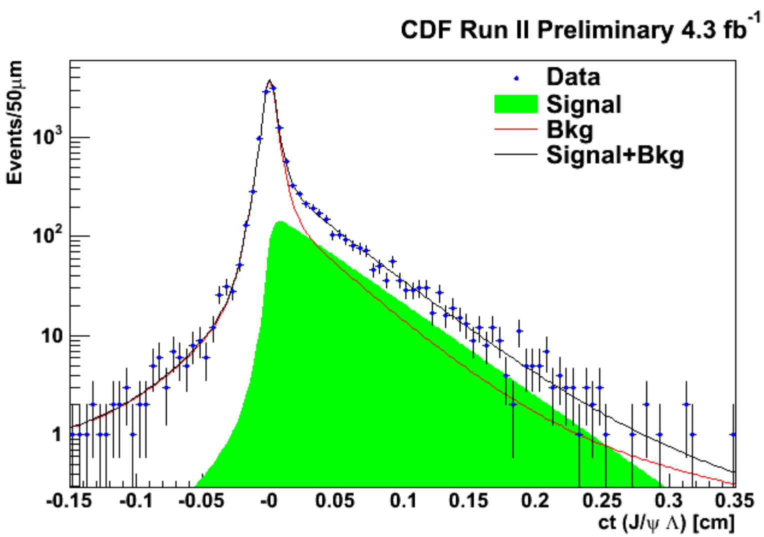
CDF : Public Note 10071

The result of the CDF update gave a high ratio of $\tau(\Lambda_b^0)$ to $\tau(B^0)$

- CDF looked at the decays $\Lambda_b^0 \to J/\psi\Lambda, B^0 \to J/\psi K^*,$ and $B^0 \to J/\psi K_S^0$
- Performed unbinned likelihood fit over mass, lifetime, and lifetime error



$$\tau(\Lambda_b^0) = 1.537 \pm 0.045(\text{stat.}) \pm 0.014(\text{syst.})\ \text{ps}$$
$$\tau(B^0) = 1.507 \pm 0.010(\text{stat.}) \pm 0.008(\text{syst.})\ \text{ps}$$

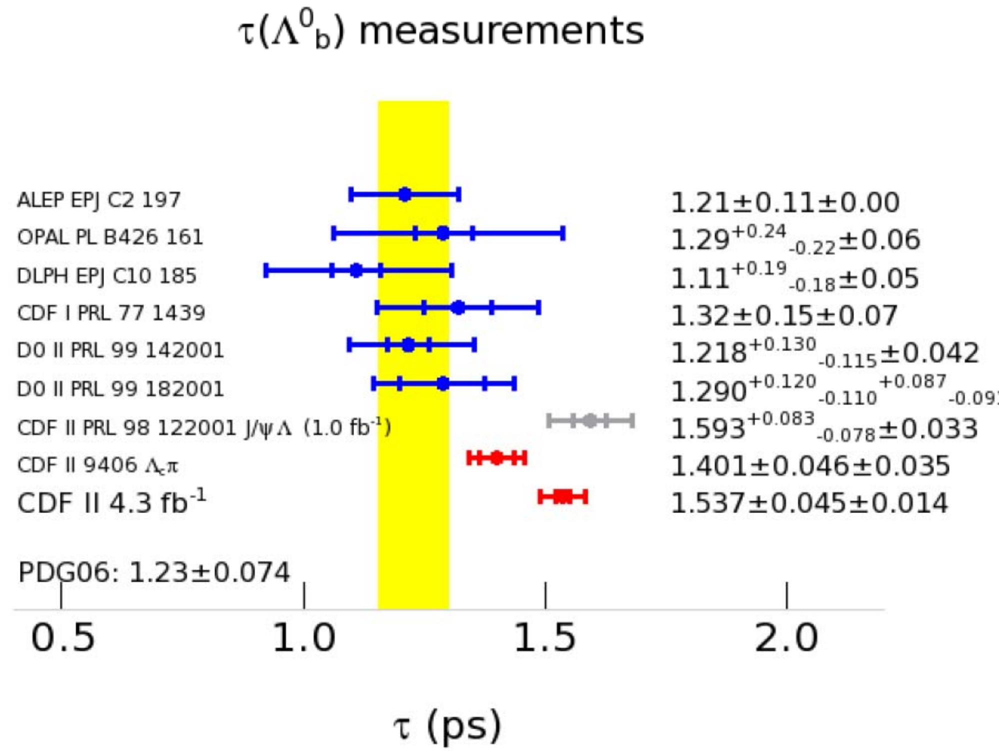


This then gives

$$\tau(\Lambda_b^0)/\tau(B^0) = 1.020 \pm 0.030\,(\text{stat.}) \pm 0.008(\text{syst.})$$

Summary of the current Λ_b^0 lifetime picture

- Currently, HQE makes the prediction of [1] $\tau(\Lambda_b^0)/\tau(B^0) = 0.88 \pm 0.05$
- Most theory uncertainty comes from non-pert. ME, improved lattice calculations could help
- Semileptonic systematically low compared to fully recon. results from CDF
- Two recent measurements from CDF are best yet
- Two CDF $\Lambda_b^0 \to J/\psi\Lambda$ results are highly correlated

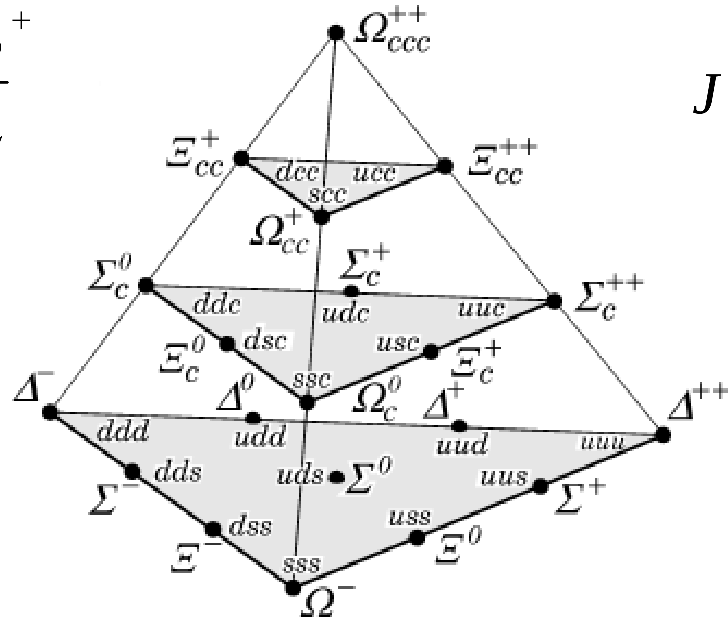


Yellow band from PDG06, doesn't have previous CDF measurements from $\Lambda_b^0 \to J/\psi\Lambda$ or $\Lambda_b^0 \to \Lambda_c^+\pi^-$

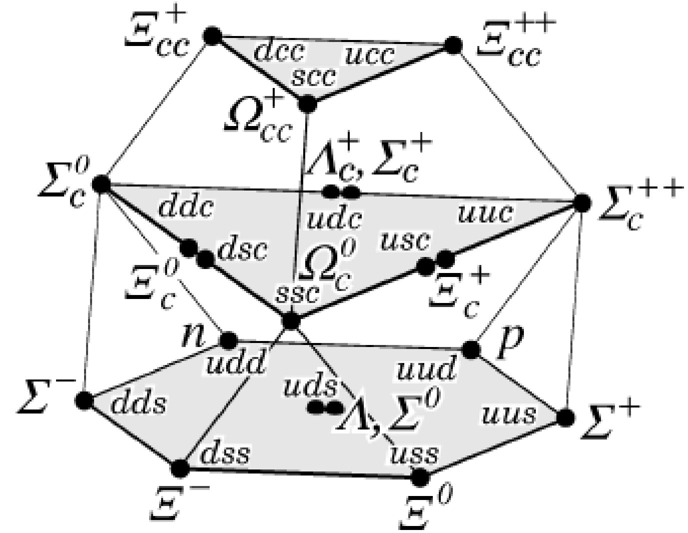
1. C.Tarantino *et al.*, arXiv:hep-ph/0310241, up to $O(1/m_b^4)$

Moving onwards toward the charmed baryons

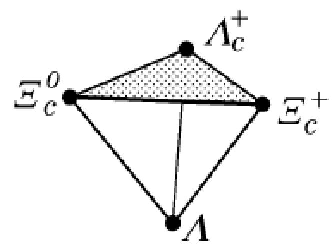
$J^P = \frac{3}{2}^+$



$J^P = \frac{1}{2}^+$



$J^P = \frac{3}{2}^-$ or $J^P = \frac{1}{2}^-$



The baryon SU(4) multiplets

CDF recently looked for resonances in $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$

CDF ends up finding

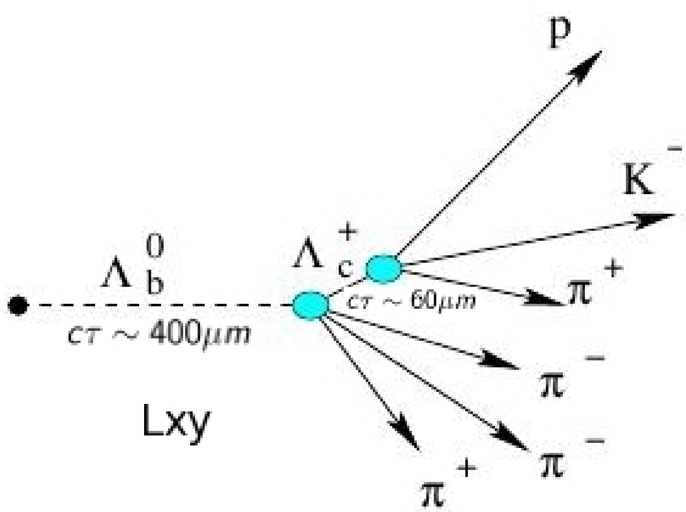
$\approx 900\ \Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$

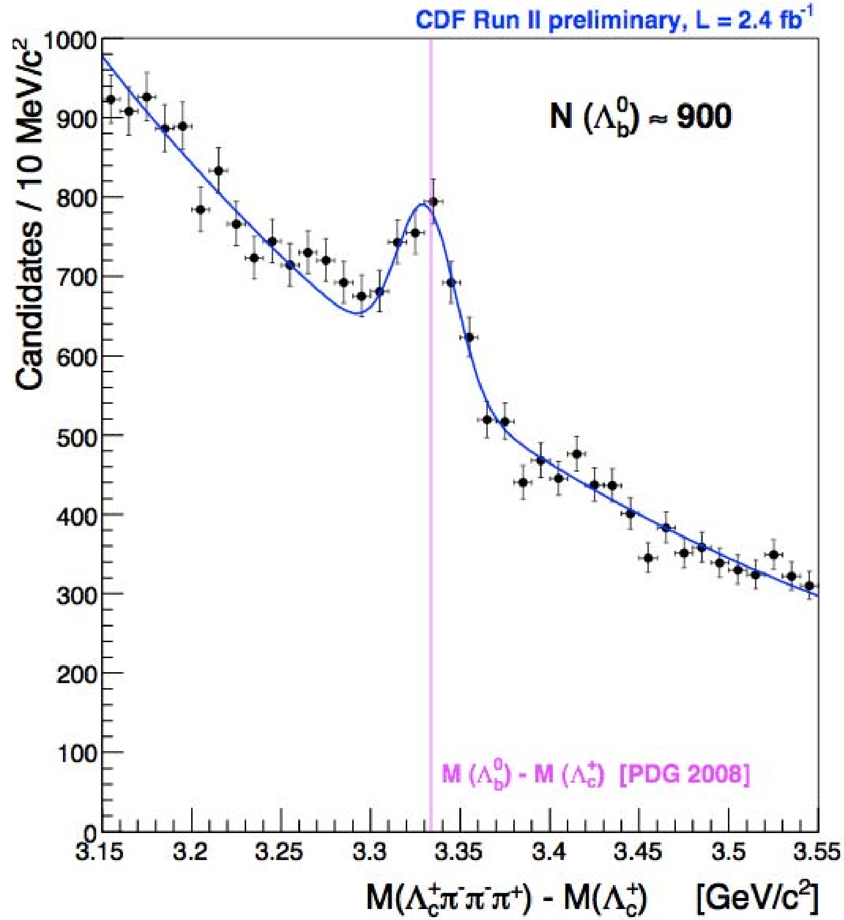
$\approx 45\ \Lambda_b^0 \to \Lambda_c^+(2595) \pi^-$

$\approx 110\ \Lambda_b^0 \to \Lambda_c^+(2625) \pi^-$

$\approx 85\ \Lambda_b^0 \to \Sigma_c^{++}(2455) \pi^- \pi^-$

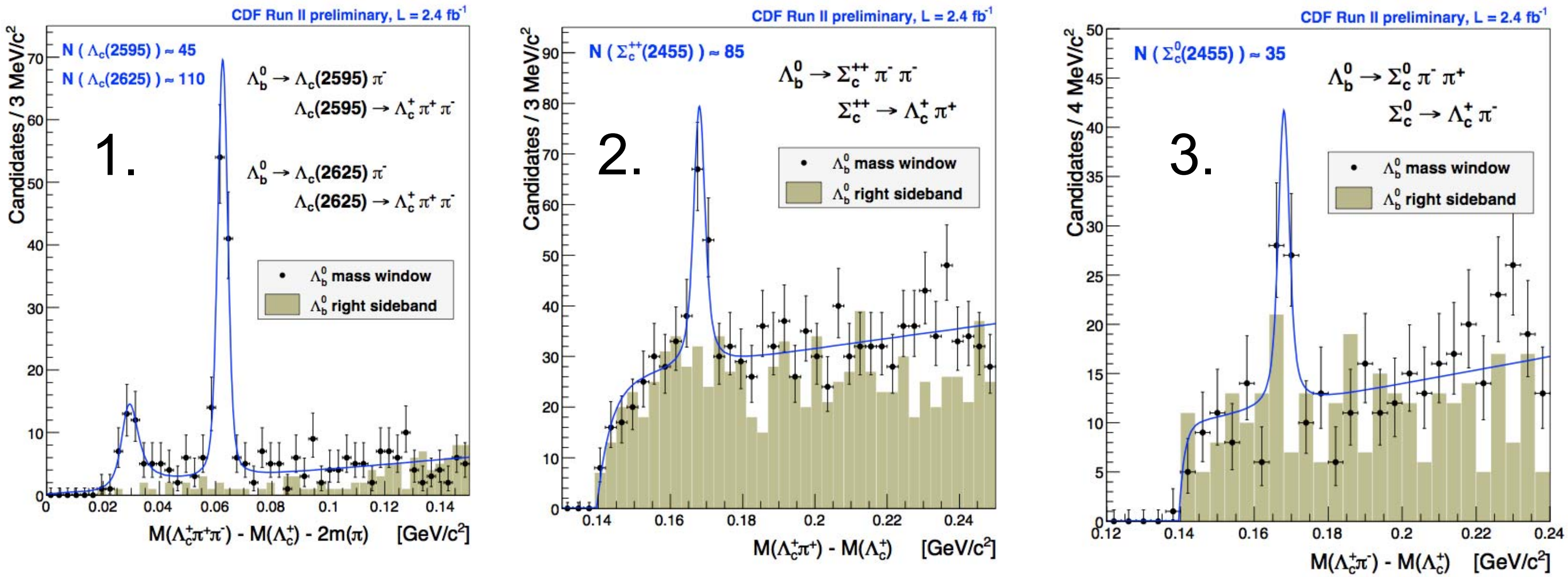
$\approx 35\ \Lambda_b^0 \to \Sigma_c^0(2455) \pi^+ \pi^-$





CDF : Public Note 10001

The mass distributions for resonances observed in $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$



The mass plots used to identify the different resonances

1. $M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+) - 2m(\pi)$ for $\Lambda_c(2595) \to \Lambda_c^+\pi^+\pi^-$ and $\Lambda_c(2625) \to \Lambda_c^+\pi^+\pi^-$
2. $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ for $\Sigma_c^{++} \to \Lambda_c^+\pi^+$
3. $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ for $\Sigma_c^{0} \to \Lambda_c^+\pi^-$

The measured branching fractions for the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ resonances

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2595)^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (2.5 \pm 0.6(stat.) \pm 0.5(syst.)) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2625)^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (6.2 \pm 1.0(stat.)^{+1.0}_{-0.9}(syst.)) \times 10^{-2}$$

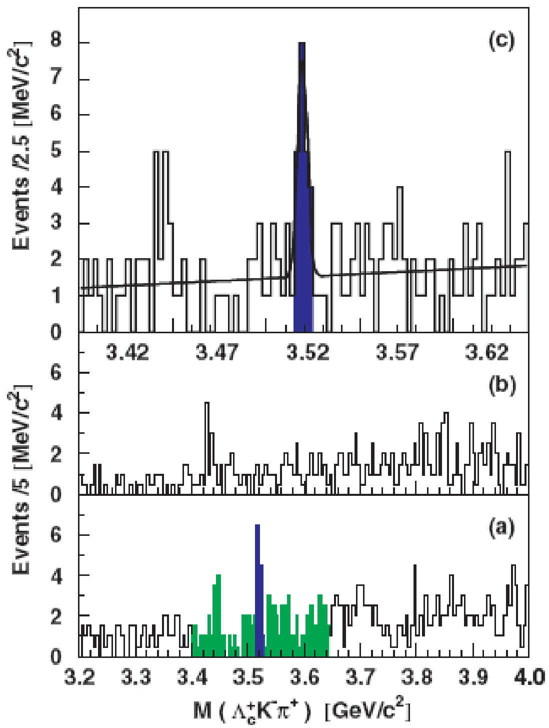
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (5.2 \pm 1.1(stat.) \pm 0.8(syst.)) \times 10^{-2}$$

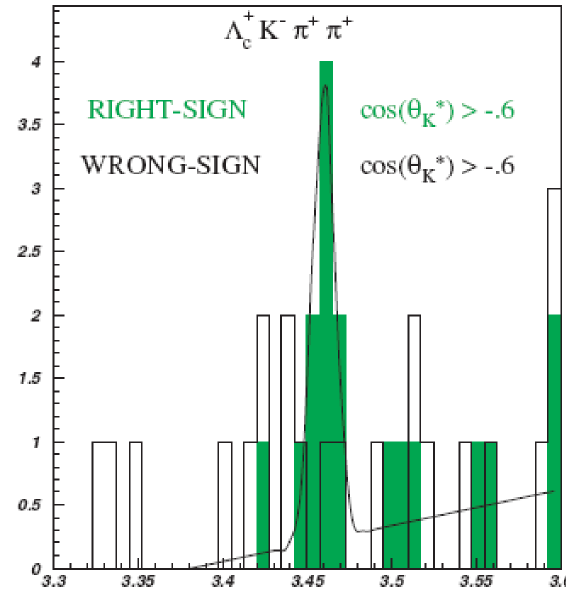
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c(2455)^{0}\pi^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (8.9 \pm 2.1(stat.)^{+1.2}_{-1.0}(syst.)) \times 10^{-2}$$

- Yields come off of an unbinned likelihood fit of mass
- Complements a previous analysis performed looking for resonant structures in $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+l^-\nu$ (see Phys. Rev. D 79, 032001(2009))

In 2002, the SELEX experiment announced the observation of doubly charmed baryons, the $\Xi_{cc}^{+}(ccd)$ and $\Xi_{cc}^{++}(ccu)$

- SELEX was a fixed target experiment at FNAL, operating on the $600\ \mathrm{GeV/c^2}$ Hyperon Beam
- The analysis looked for decays of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ and $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$[a].





- Found 22 $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ events and 9 $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$ events
- They measure the masses as $3520\ \mathrm{MeV/c^2}$ for Ξ_{cc}^{+} and $3460\ \mathrm{MeV/c^2}$ for the Ξ_{cc}^{++}
- The mass difference of $60\ \mathrm{MeV/c^2}$ is too large for the same isospin doublet

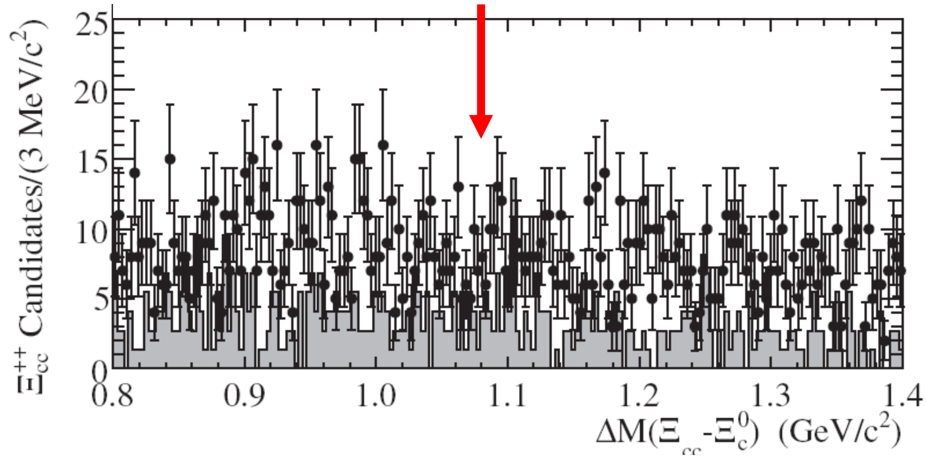
SELEX : arXiv : hep-ex/0212029

a. SELEX updated with additional channels $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}, pD^{+}K^{-}$, and $\Xi_{cc}^{++} \to \Xi_c^{+} \pi^{-} \pi^{+} \pi^{+}$

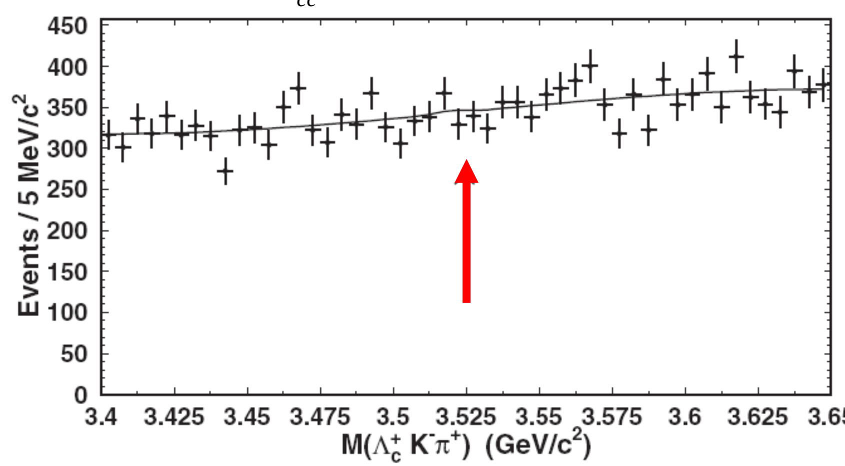
Thus far, attempts to confirm the SELEX result have turned up nothing

- BABAR looked for Ξ_{cc}^{+} in $\Lambda_c^+ K^- \pi^+$ and $\Xi_c^0 \pi^+$, and for Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^0 \pi^+ \pi^+$
- BELLE looked for Ξ_{cc}^{+} in $\Lambda_c^+ K^- \pi^+$
- Both experiments reported back the null result for their respective searches
- Theory could help, though it might be tough for CDF/D0
  - Difficulty lies in triggering on them, lifetimes are short and they don't arise from Λ_b^0 decays

BABAR for Ξ_{cc}^{++}



BELLE for Ξ_{cc}^{+}

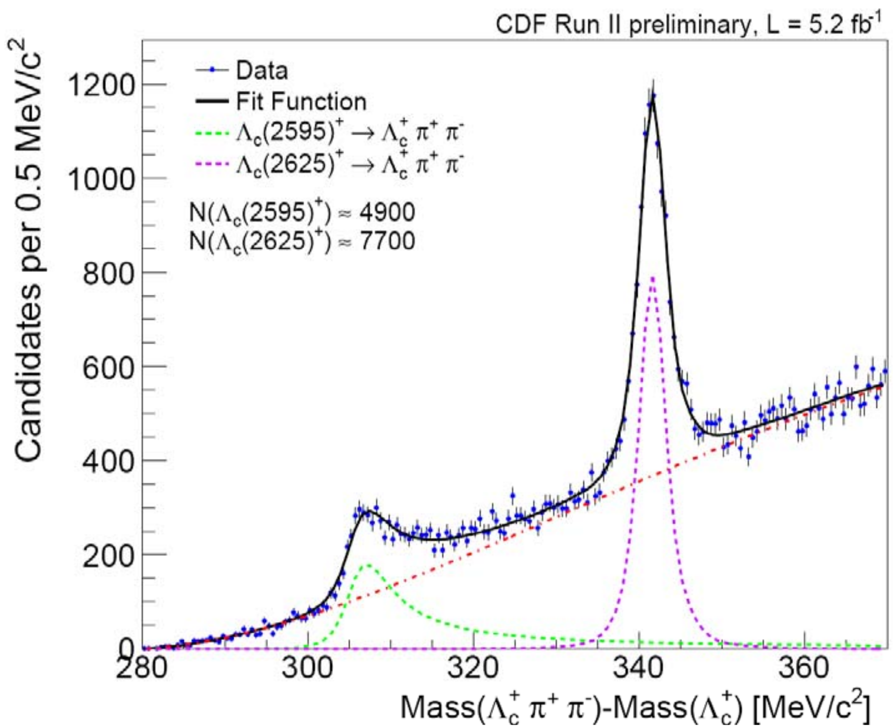


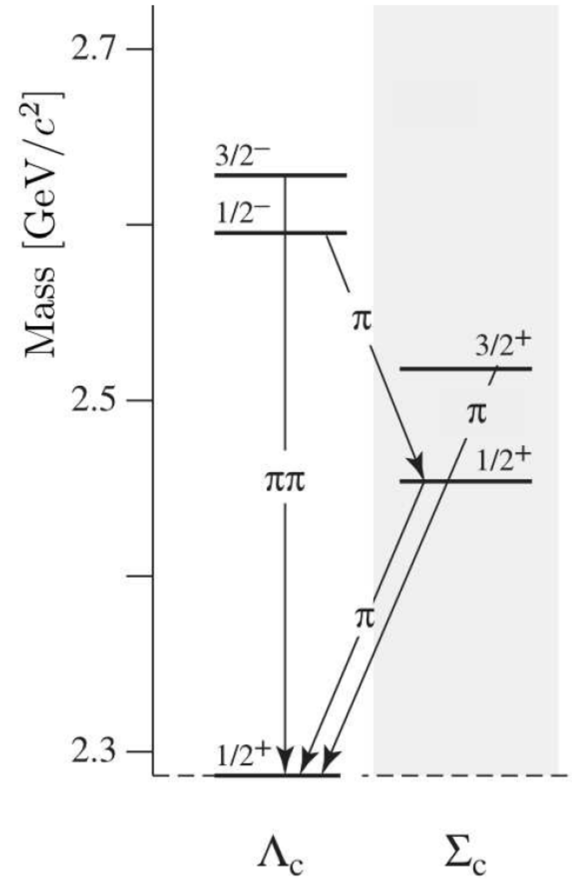
BABAR: Phys. Rev. D 74, 011103(R) (2006)

BELLE: Phys. Rev. Lett. 97, 162001 (2006)

CDF is further examining the excited charm baryon states of $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, and $\Sigma_c(2520)$

- Aims to measure widths and masses with respect to $\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$ and $\Sigma_c^{0/++} \to \Lambda_c^+\pi^{-/+}$
- Analysis uses 5.3 fb^{-1} off of the hadronic trigger
- Begins by reconstructing $\Lambda_c^+ \to p^+K^-\pi^+$ then adding tracks under π mass hypothesis



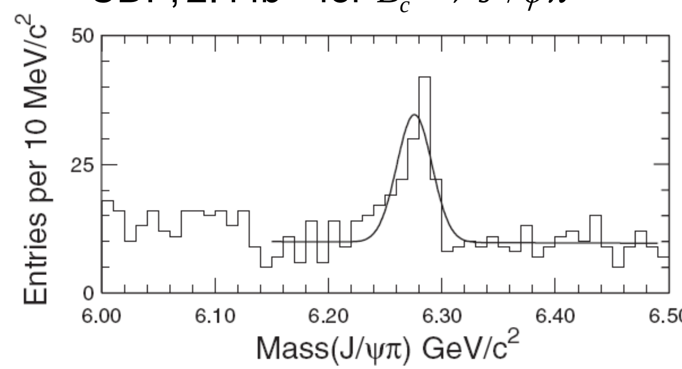


Mass fit from CDF PR blessing

Summary

- Lots of good measurements
  - Charm spectroscopy
  - b - baryon lifetimes
- Some discrepancies
  - The Ω_b^- mass measurement, hopefully resolved with D0 update
  - The SELEX result for doubly charmed baryons
- Interesting future
  - The double heavy states are a stretch (e.g. $|bcu>$ and $|bcd>$), could potentially see a handful in ~ 10 fb^{-1} based on $B_c^+ \to J/\psi\pi^+$ (108 cand. in 2.4 fb^{-1})

CDF, 2.4 fb^{-1} for $B_c^+ \to J/\psi\pi^+$



CDF : Phys. Rev. Lett. 100, 182002 (2008)

Backup slides

How do the rates for the Ω_b^- compare between CDF and D0?

D0 measures

$$\frac{f(b \rightarrow \Omega_b^-)BR(\Omega_b^- \rightarrow J/\psi\Omega^-)}{f(b \rightarrow \Xi_b^-)BR(\Xi_b^- \rightarrow J/\psi\Xi^-)} = 0.80 \pm 0.32(\text{stat.}) \pm^{+0.14}_{-0.22} (\text{syst.})$$

CDF measures

$$\frac{\sigma(\Omega_b^-)BR(\Omega_b^- \rightarrow J/\psi\Omega^-)}{\sigma(\Xi_b^-)BR(\Xi_b^- \rightarrow J/\psi\Xi^-)} = 0.27 \pm 0.12(\text{stat.}) \pm 0.01(\text{syst.})$$

- Large errors, ratio of small samples taken
- CDF does measure a much smaller rate