FPCP 2007, Bled

New Heavy Quark Baryons

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Why heavy baryon spectroscopy

- Heavy Quark mesons are QCD analog of "hydrogen atom"
  - $\longrightarrow$ Starts to be very sensitive test of various model in non-perturbative regime of QCD
  - $\longrightarrow$ Lot of information in charm sector
  - $\longrightarrow$ Bottom sector starts to speak up as well
- Heavy Quark baryon are next interesting laboratory
  - $\longrightarrow$ Heavy quark - light diquark is basic picture
  - $\longrightarrow$ Another sensitive test of models
  - $\longrightarrow$ Still many things to observe in charm sector
  - $\longrightarrow$ In bottom sector only Λ_b directly seen
- Discovery of new particles is exciting and fun

Where to study heavy baryons

- Everywhere where we produce them and have detector to detect them
- Current results come from

$\longrightarrow$ B-factories (Belle, *BABAR*)

+ Have large amount of data
+ Clean environment
– Bound to charm sector

$\longrightarrow$ Tevatron (CDF)

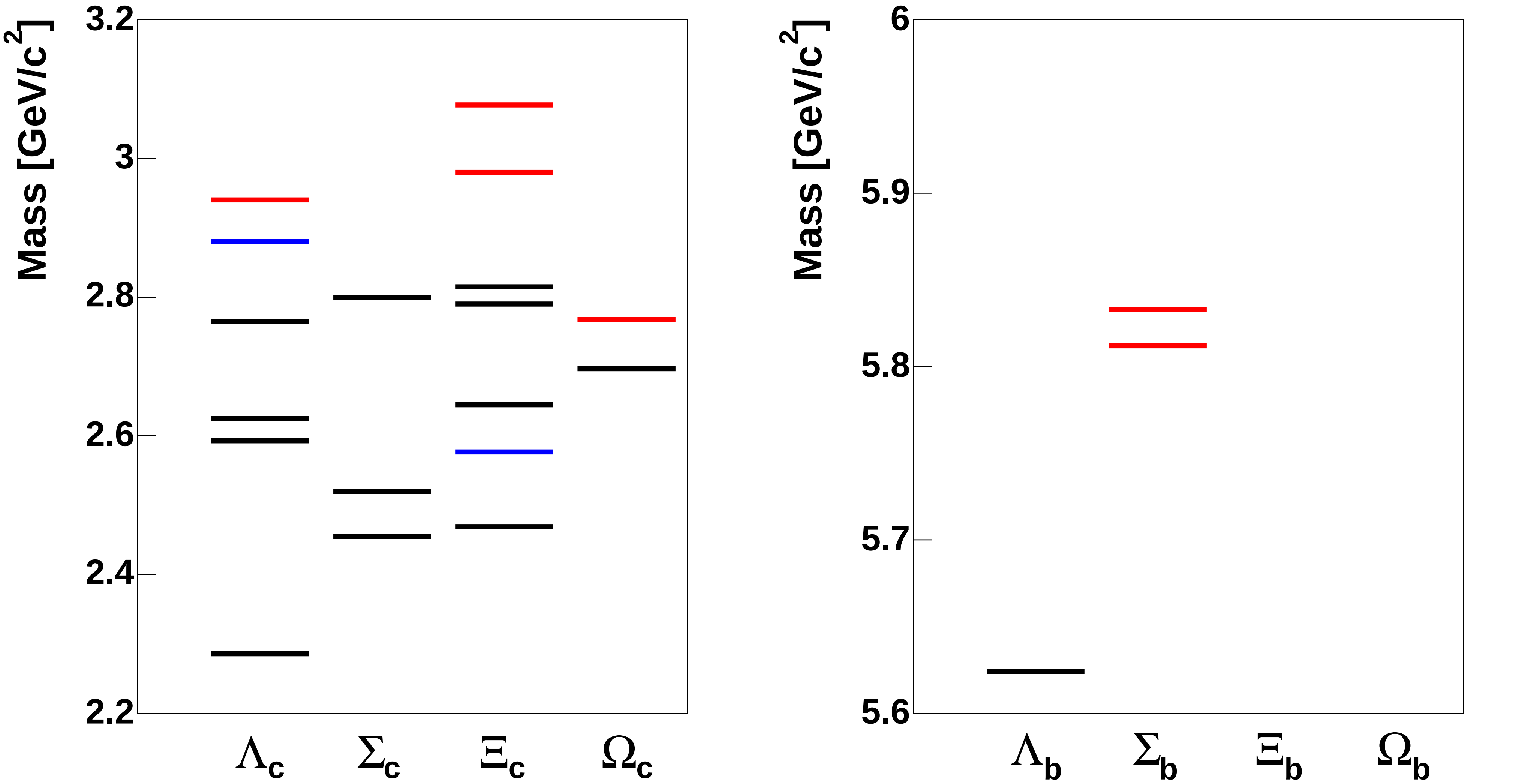
– Difficult environment from $p\bar{p}$ collisions
– Only now starts to have reasonable amount of data for b-baryons
+ Can do all b-hadrons

Directly observed states

Listed in PDG 2006

Listed in PDG 2006, but new results

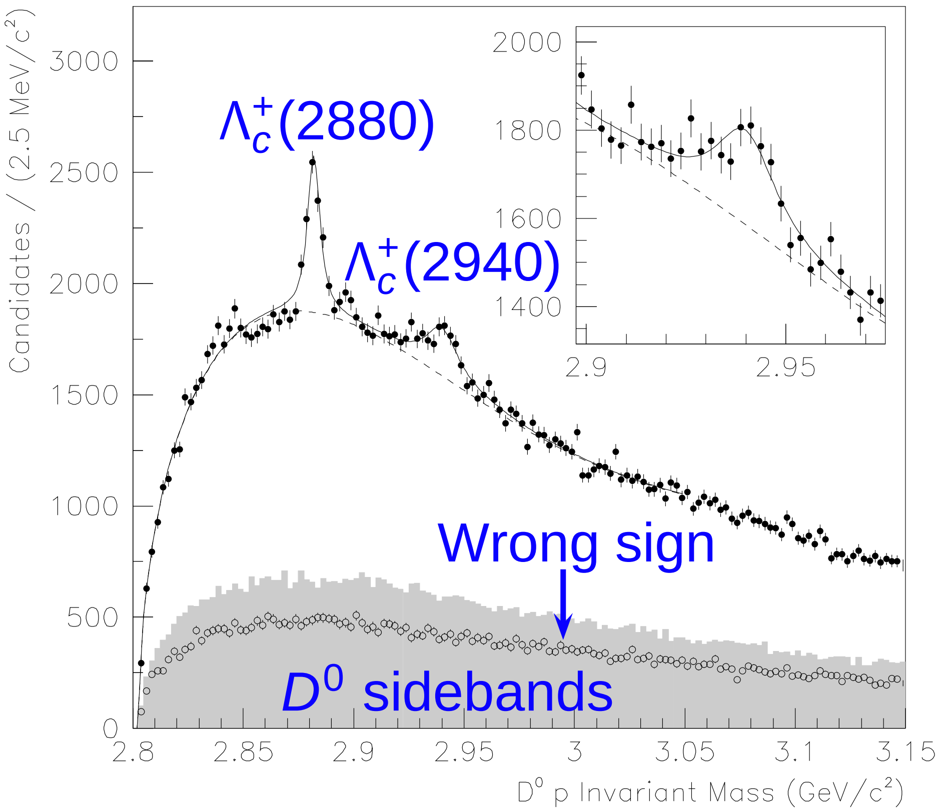
Not in PDG 2006, covered here

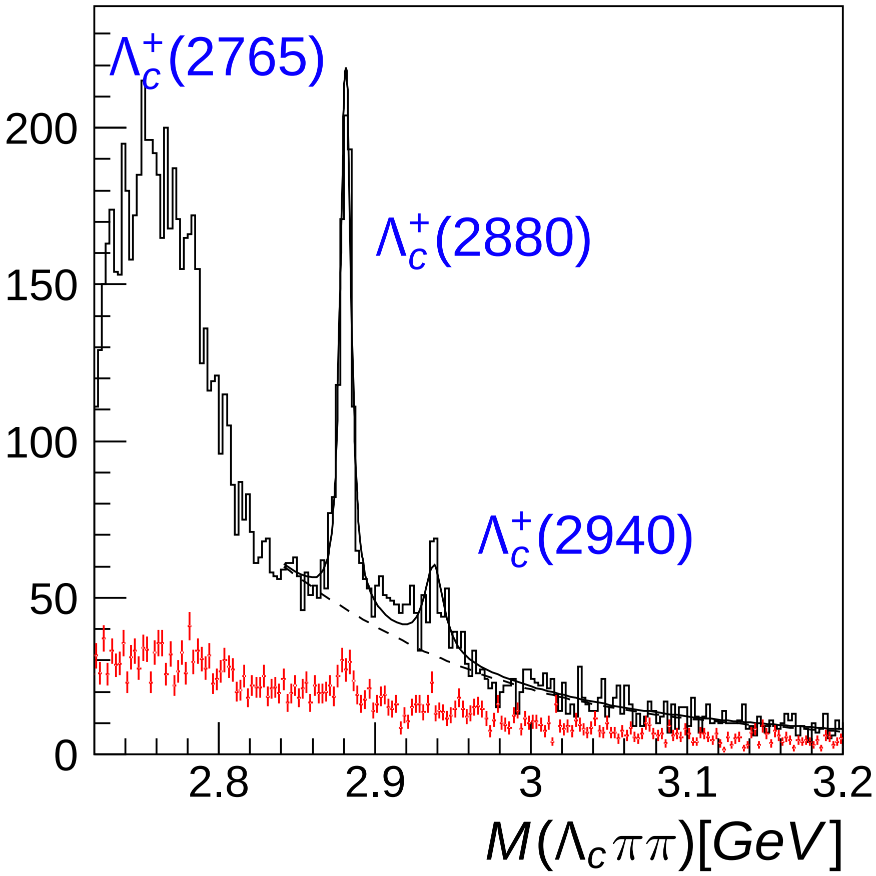


$\Lambda_c^+(2880)$, $\Lambda_c^+(2940)$

- 287 fb^{-1} of data
- $p\,D^0$ final state
- $D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$
- PRL 98, 012001 (2007)

- 553 fb^{-1} of data
- Confirmation in $\Lambda_c^+\pi^+\pi^-$
- $\Lambda_c^+\pi^\pm$ consistent with $\Sigma_c(2455)$
- hep-ex/0608043





$\Lambda_c^+(2880)$, $\Lambda_c^+(2940)$

- $\Lambda_c(2880)$ known state, but pD^0 decay is new
- $\Lambda_c(2940)$ observed for the first time
- Significance 7.5 σ at *BABAR* and 6.2 σ at Belle
- Mass and width consistent between experiments

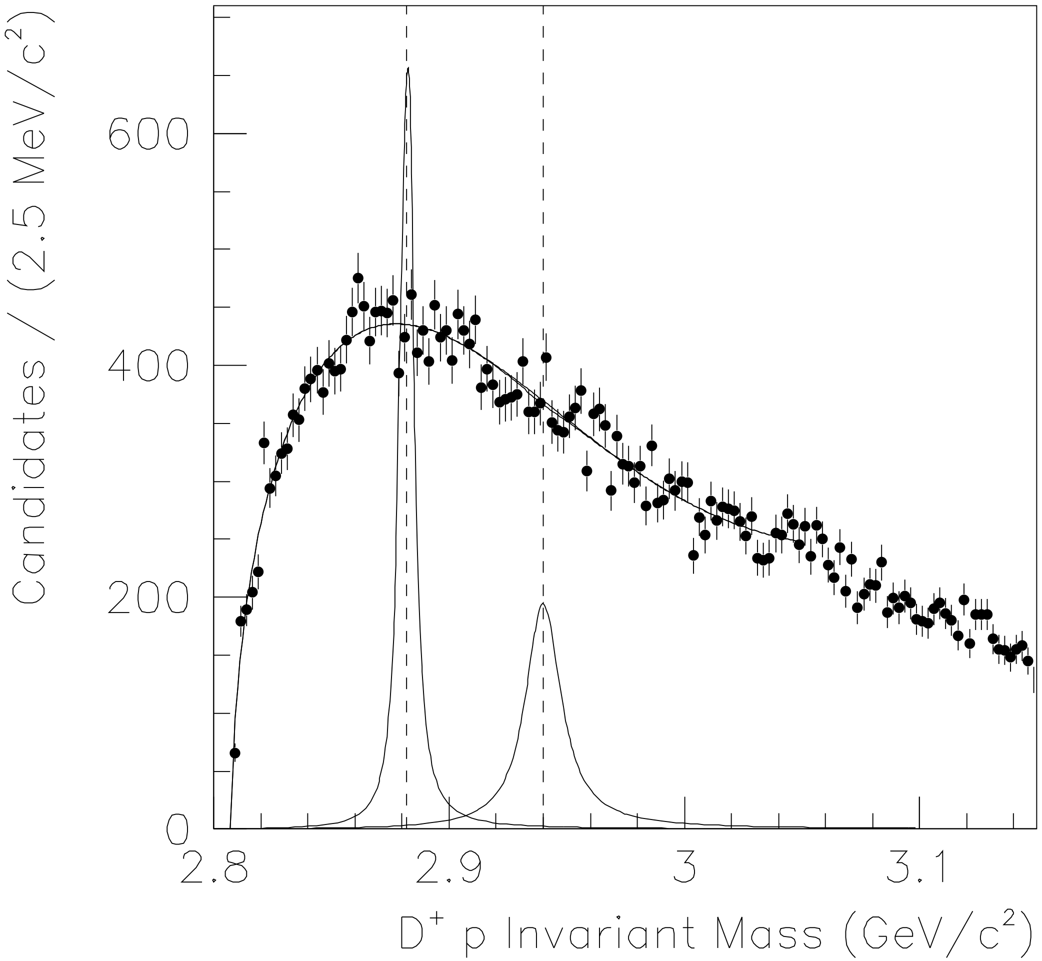
	State	Mass [MeV/c^2]	Width [MeV/c^2]
BABAR	$\Lambda_c(2880)$	$2882 \pm 0.1 \pm 0.5$	$5.8 \pm 1.5 \pm 1.1$
Belle	$\Lambda_c(2880)$	$2881.2 \pm 0.2 \pm 0.4$	$5.5 \pm 0.7 \pm 1.1$
BABAR	$\Lambda_c(2940)$	$2939.8 \pm 1.3 \pm 1.0$	$17.5 \pm 5.2 \pm 5.9$
Belle	$\Lambda_c(2940)$	$2938.0 \pm 1.3^{+2.0}_{-4.0}$	$13\,^{+8}_{-5}\,^{+27}_{-7}$

- To learn more, both experiments do further studies

  $\rightarrow$ *BABAR* checks isospin partners

  $\rightarrow$ Belle studies resonant substructure of decay and angular distributions

$\Lambda_c^+(2880)$, $\Lambda_c^+(2940)$



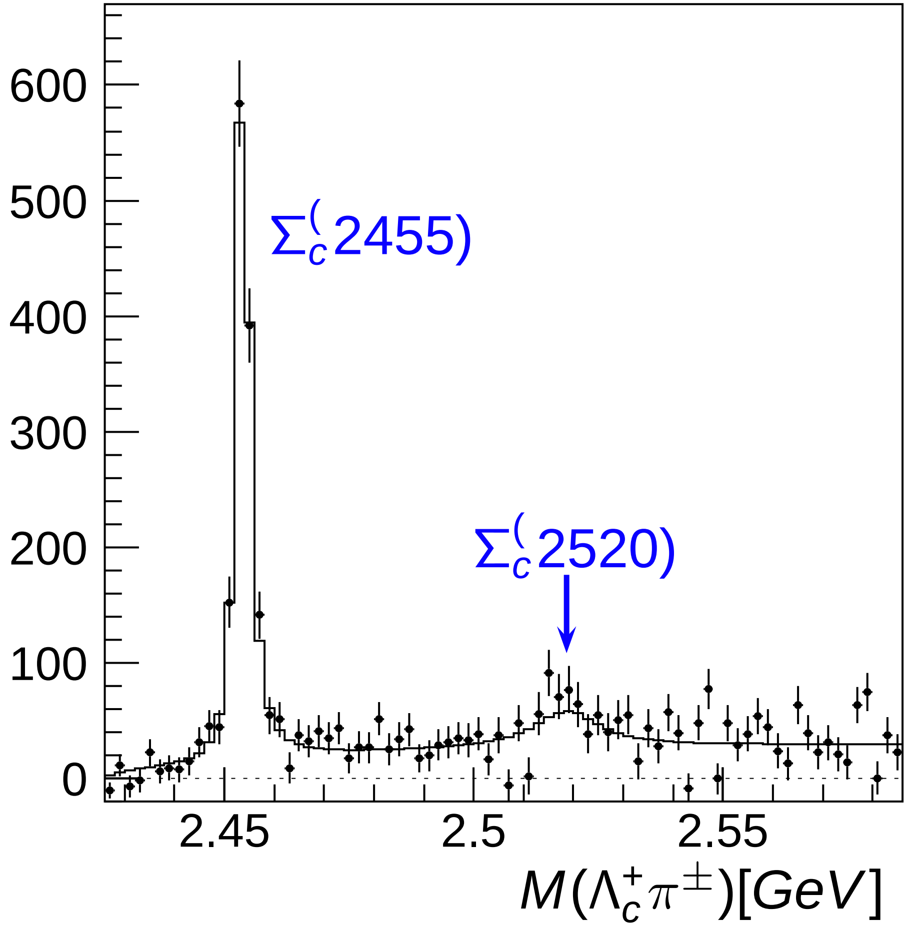
Curves same rate as pD^0

- $\rightarrow$ If $\Sigma_c \Rightarrow$ also $\Sigma_c^{++} \rightarrow D^+p$
  $D^+ \rightarrow K\pi\pi$
- $\rightarrow$ No resonant structure seen
- $\Rightarrow$ Both states are Λ_c's
- 3 Λ_c states predicted $\approx$ 2940 MeV$/c^2$
  $J^P = (1/2)^+, (1/2)^-, (3/2)^-$
  Migura et al, Eur.Phys.J. A28 (2006) 41
- The $\Lambda_c(2880)^+$ is near a predicted $(3/2)^-$ state.
- Details PRL 98, 012001 (2007)

$\Lambda_c^+(2880)$

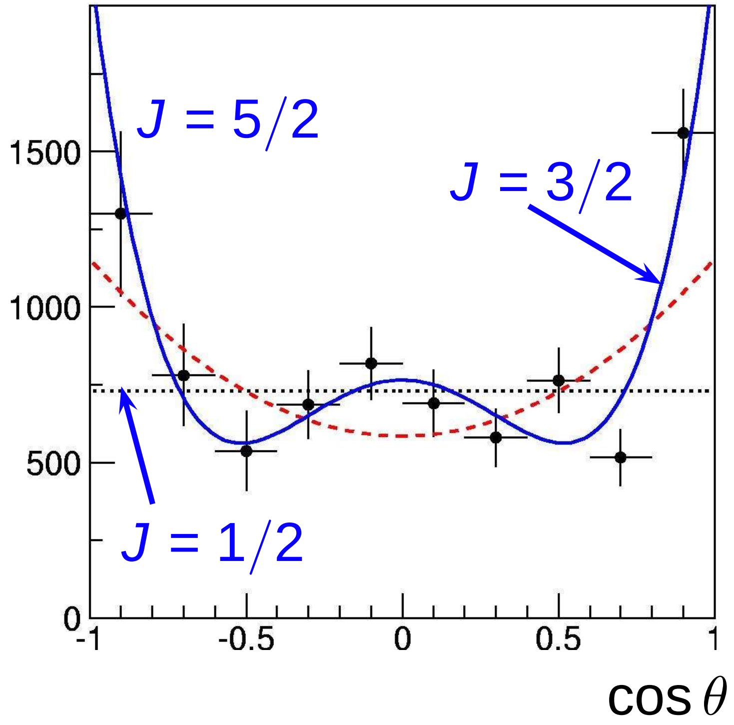
Fit $\Lambda_c(2880)$ yield in bins of $M(\Lambda_c^+\pi^\pm)$

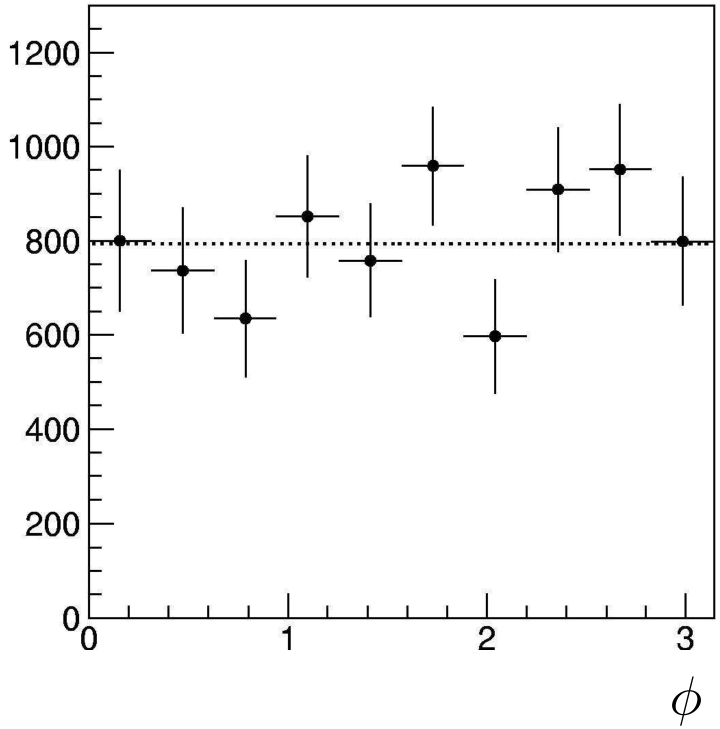
Details: hep-ex/0608043



- Significance of $\Lambda_c(2880) \to \Sigma_c(2520)\pi$ 3σ with syst.
- $\Gamma(\Sigma_c(2455)\pi)/\Gamma(\Lambda_c\pi\pi) = 40.4 \pm 2.1 \pm 1.4\%$
- $\Gamma(\Sigma_c(2520)\pi)/\Gamma(\Lambda_c\pi\pi) = 9.1 \pm 2.5 \pm 1.0\%$
- $\Gamma(\Sigma_c(2520)\pi)/\Gamma(\Sigma_c(2455)\pi) = 22.5 \pm 6.2 \pm 2.5\%$

$\Lambda_c^+(2880)$





- Fit $\Lambda_c(2880)$ mass distribution in angular bins and subtract non-resonant contribution
- χ^2/ndf.: 46.7/9 ($J = 1/2$); 35.1/8 ($J = 3/2$); 12.1/7 ($J = 5/2$)
- From χ^2 difference exclude $J = 1/2$ ($J = 3/2$) by 5.5 σ (4.8 σ)
- HQS expectations for $\Gamma(\Sigma_c(2520)\pi)/\Gamma(\Sigma_c(2455)\pi)$: 140% ($J^P = 5/2^-$) and 23 – 36% ($J^P = 5/2^+$)

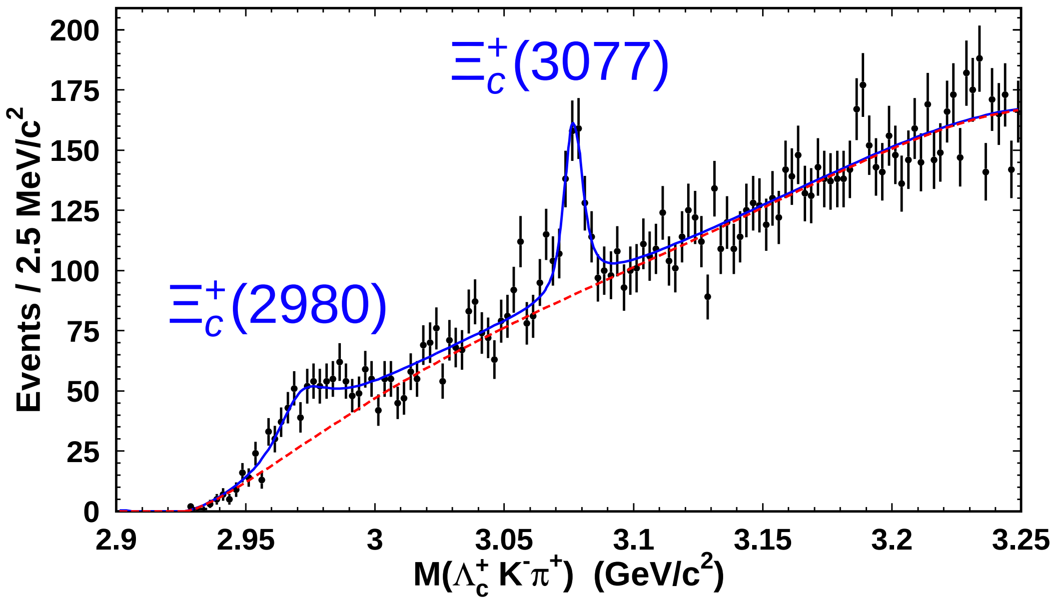
$\Xi_c(2980)$, $\Xi_c(3077)$

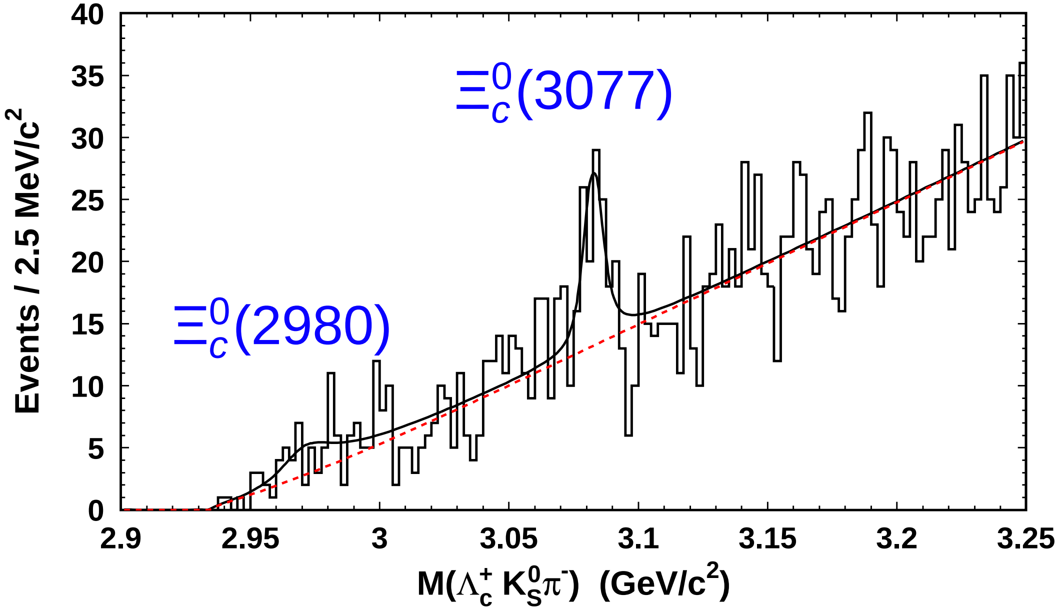
- Belle searches for new states in $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_s^0 \pi^+$
- Uses 462 fb^{-1} of data
- $\Lambda_c^+ \to p K^- \pi^+$ decay
- Signal events:

$\Xi_c^+(2980)$	405.3 ± 50.7
$\Xi_c^+(3077)$	326.0 ± 39.6
$\Xi_c^0(2980)$	42.3 ± 23.8
$\Xi_c^0(3077)$	67.1 ± 19.9

- Significance:

$\Xi_c^+(2980)$	5.7σ
$\Xi_c^+(3077)$	9.2σ
$\Xi_c^0(2980)$	1.5σ
$\Xi_c^0(3077)$	4.4σ





Details in PRL 97, 162001 (2006)

$\Xi_c(2980)$, $\Xi_c(3077)$

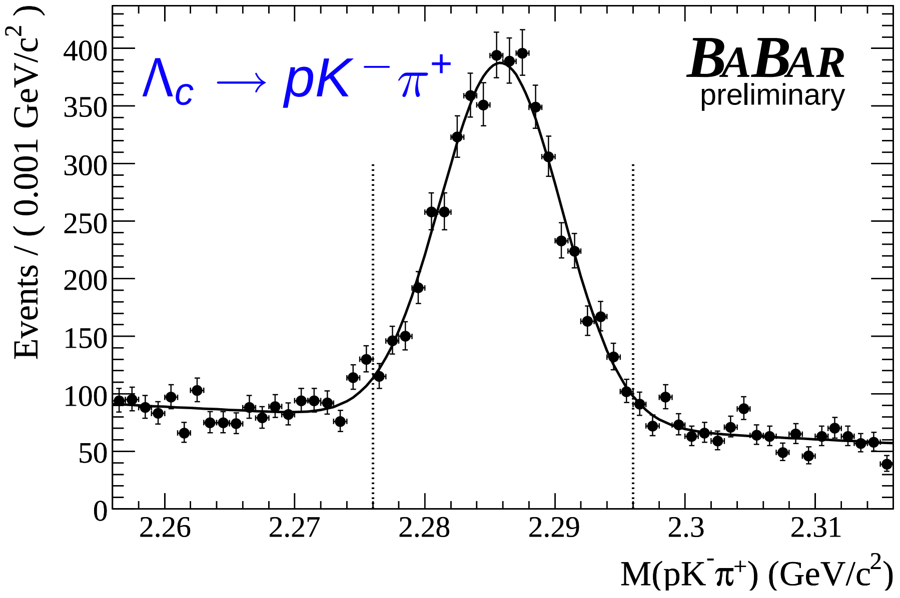
- Using 289 fb^{-1} of data *BABAR* confirms Belle's observation
- Study only $\Lambda_c^+ K^- \pi^+$ with $\Lambda_c^+ \to p K^- \pi^+$ decays
- Observes two structures in mass difference spectra
- Number of signal events

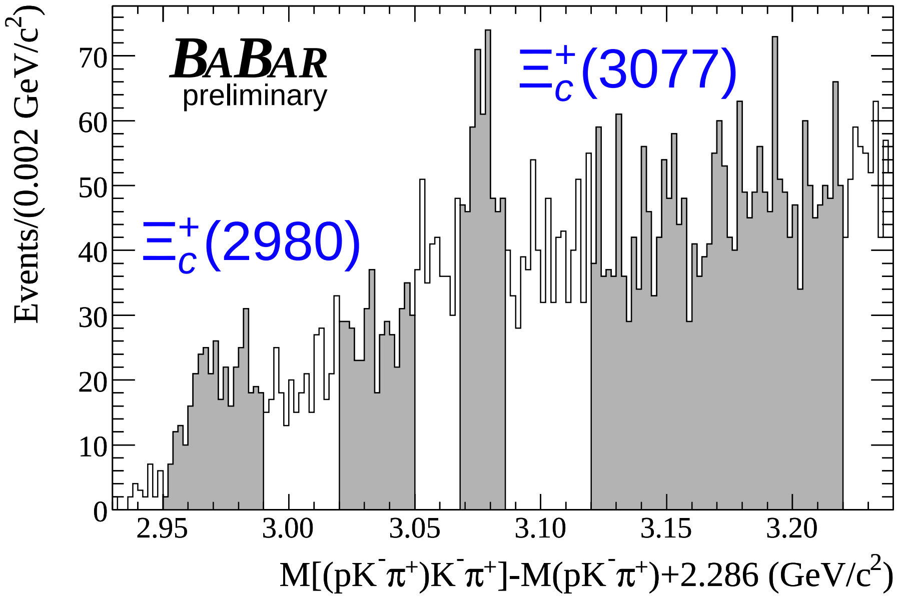
$\Xi_c^+(2980)$	$284 \pm 45 \pm 46$
$\Xi_c^+(3077)$	$204 \pm 35 \pm 12$

- Significance

$\Xi_c^+(2980)$	$7.0\,\sigma$
$\Xi_c^+(3077)$	$8.6\,\sigma$

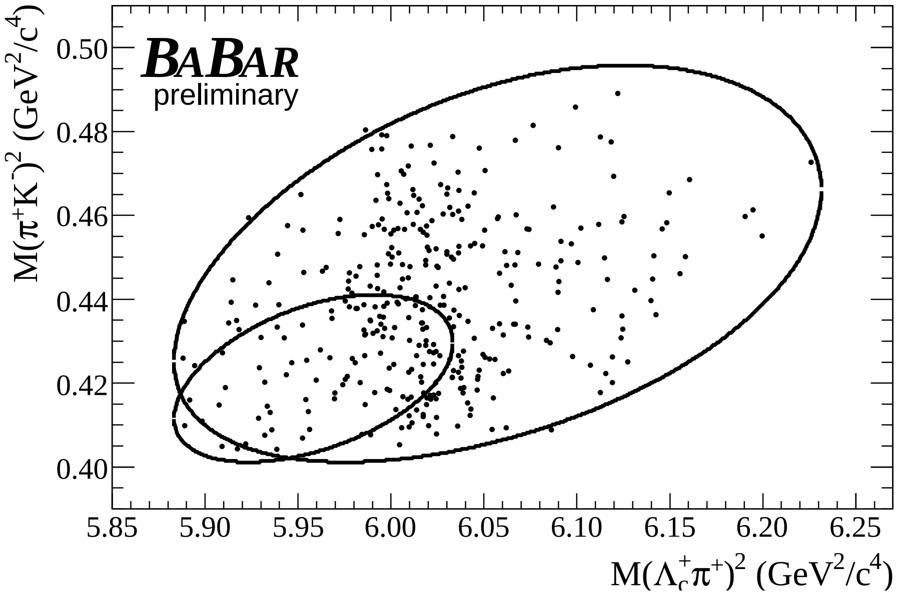
- Details in hep-ex/0607042



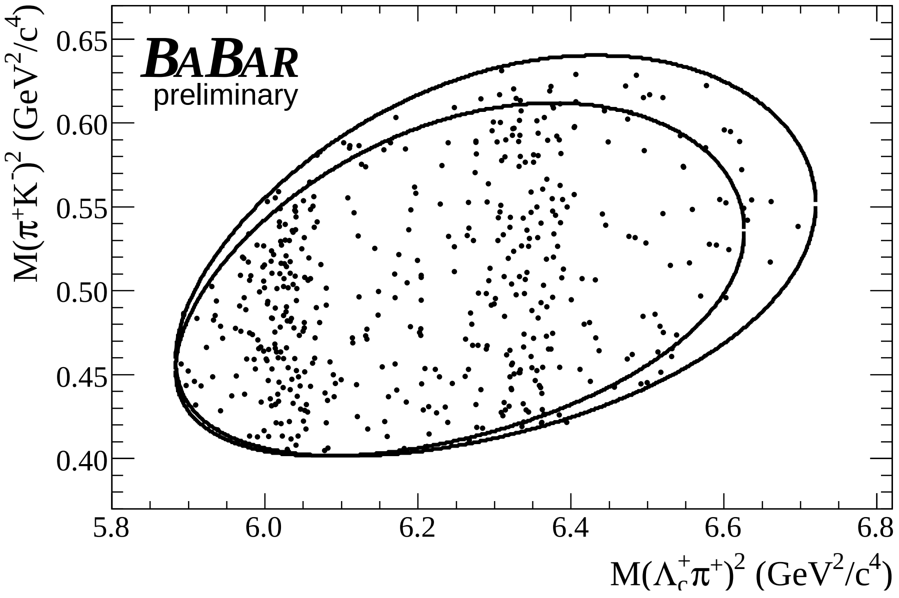


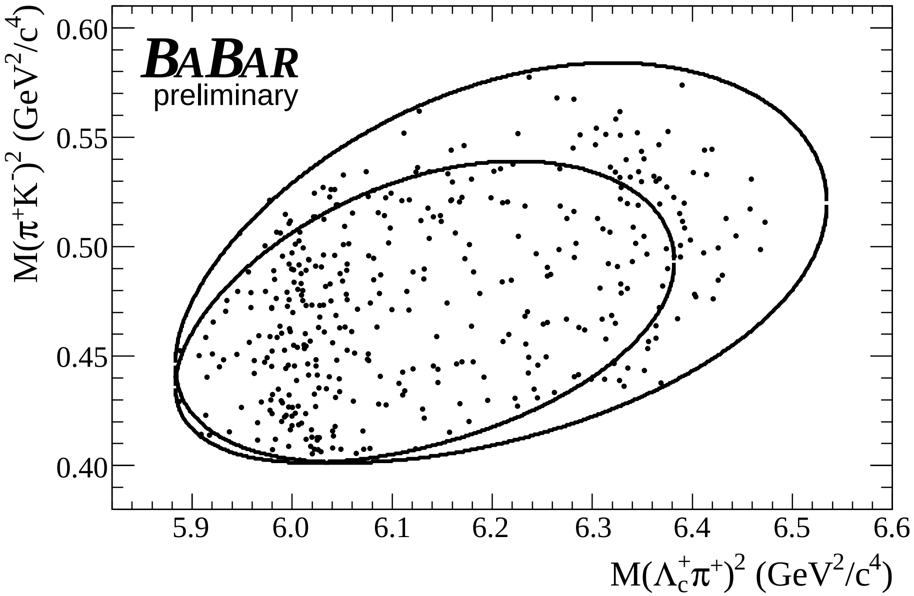
$\Xi_c(2980)$, $\Xi_c(3077)$

$2.95 < M_{\Xi_c} < 2.99$ GeV

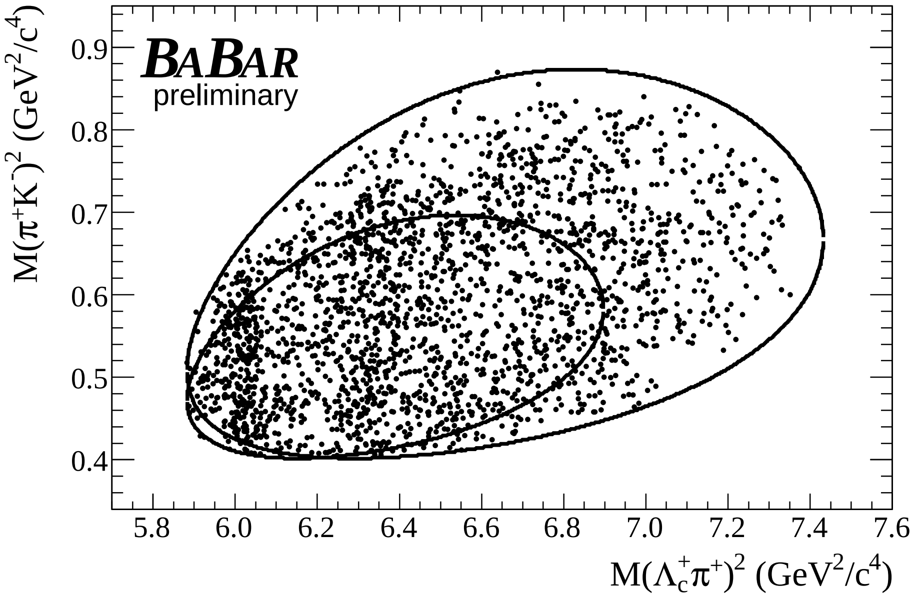


$3.07 < M_{\Xi_c} < 3.09$ GeV



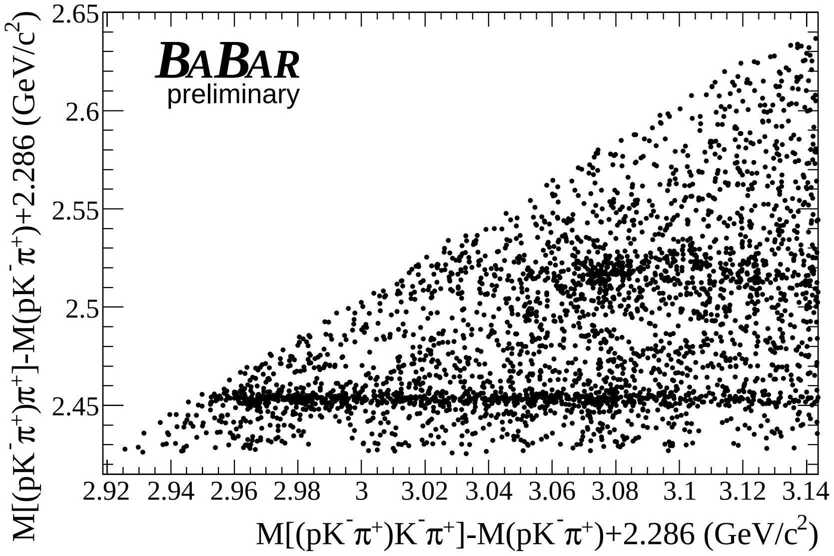


$3.02 < M_{\Xi_c} < 3.05$ GeV

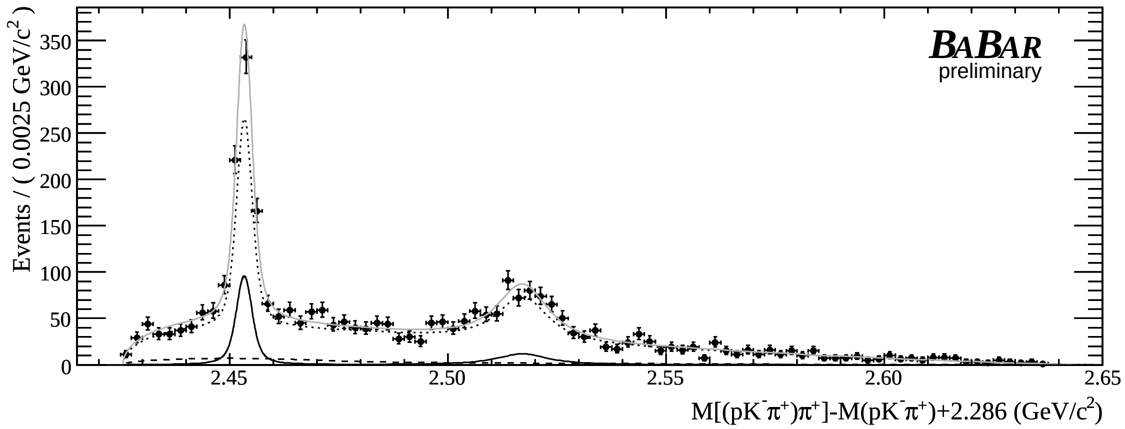


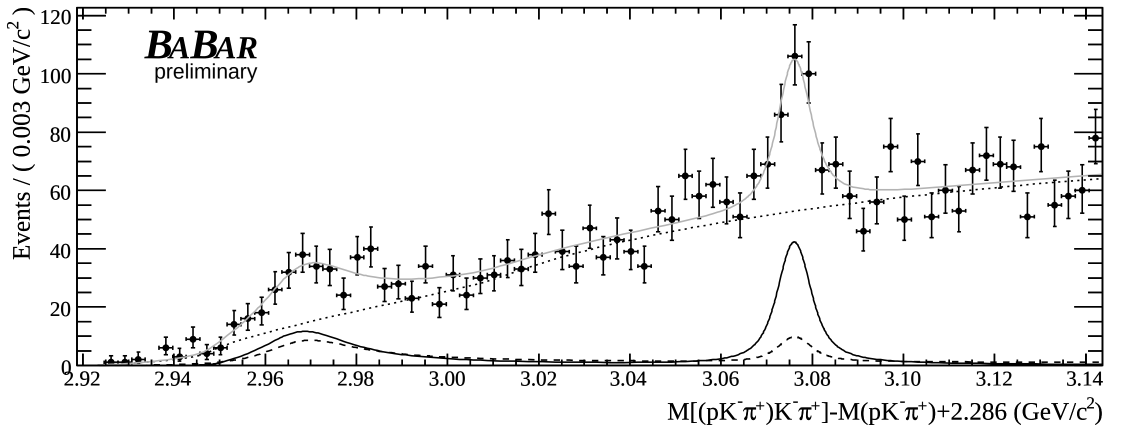
$3.12 < M_{\Xi_c} < 3.22$ GeV

$\Xi_c(2980)$, $\Xi_c(3077)$



- 2D fit to $M(\Lambda_c^+\pi^+)$ and $M(\Lambda_c^+K^-\pi^+)$
- Fit for resonance substructure of Ξ_c decays
- Allow for Σ_c states also in background





$\Xi_c(2980)$, $\Xi_c(3077)$

- *BABAR* and Belle measure consistent masses and widths

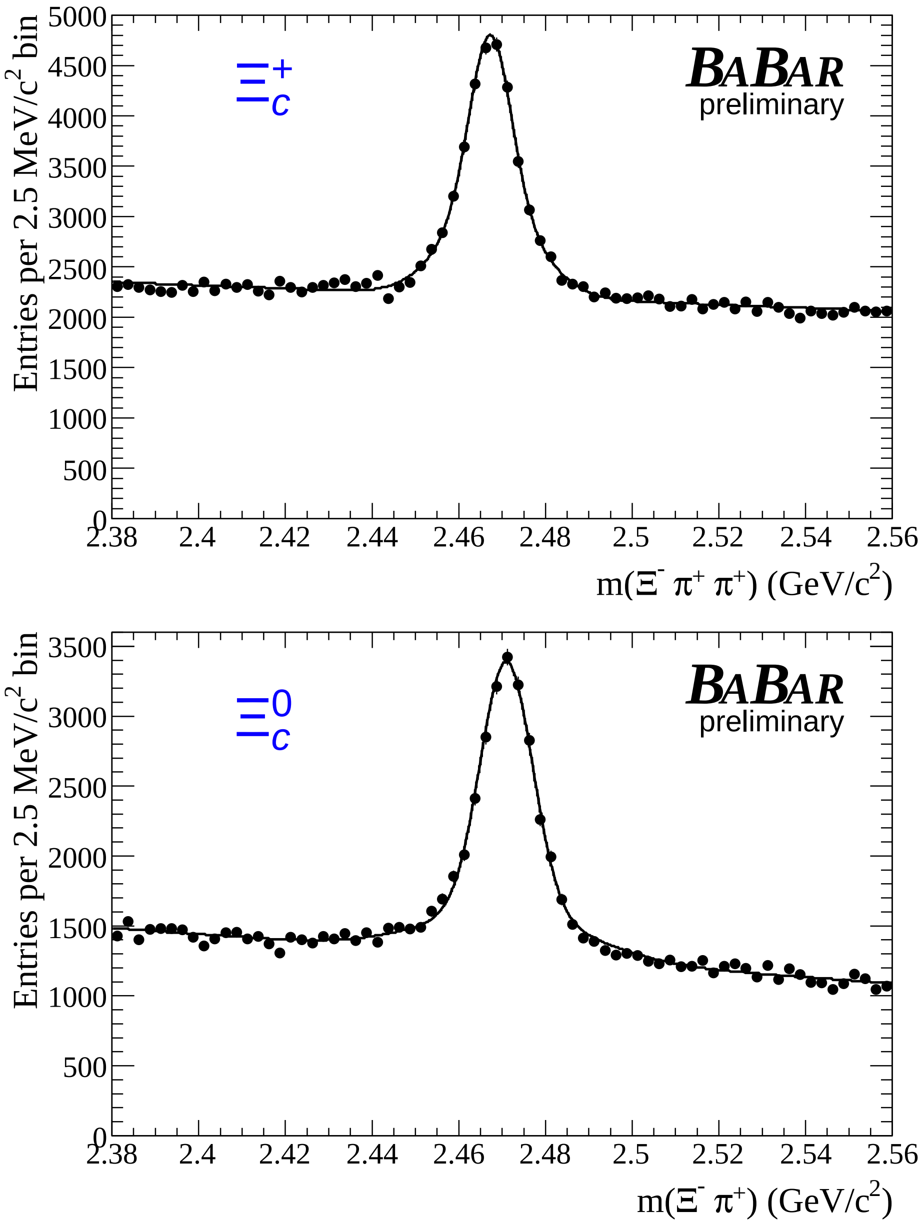
	State	Mass [MeV/c^2]	Width [MeV/c^2]
Belle	$\Xi_c^0(2980)$	$2977.1 \pm 8.8 \pm 3.5$	43.5 (fixed)
Belle	$\Xi_c^+(2980)$	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$
BABAR	$\Xi_c^+(2980)$	$2967.1 \pm 1.9 \pm 1.0$	$23.6 \pm 2.8 \pm 1.3$
Belle	$\Xi_c^0(3077)$	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$
Belle	$\Xi_c^+(3077)$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$
BABAR	$\Xi_c^+(3077)$	$3076.4 \pm 0.7 \pm 0.3$	$6.2 \pm 1.6 \pm 0.5$

- *BABAR* adds resonant substructure

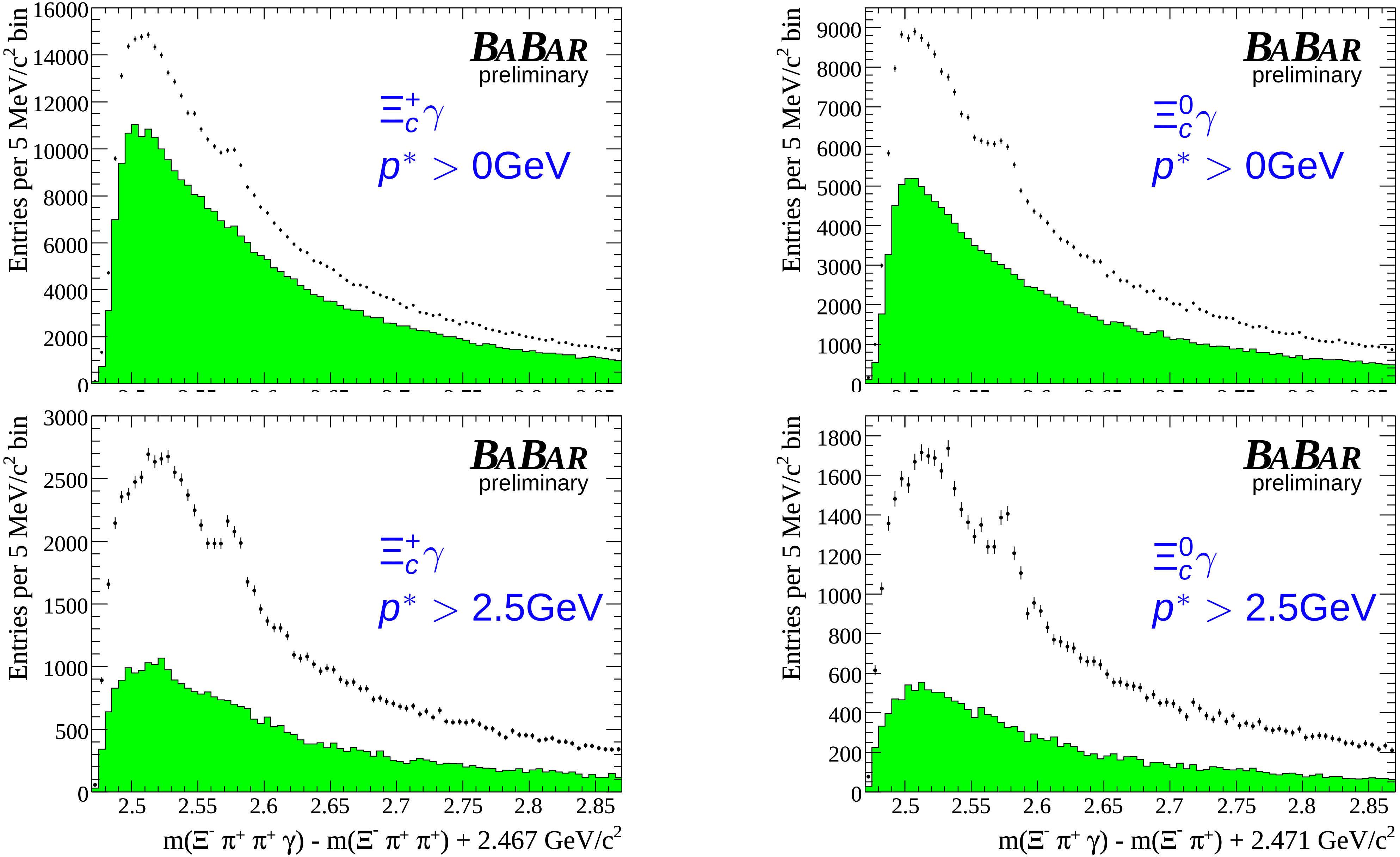
$\Xi_c^+(2980) \to \Sigma_c^{++}(2455)K^-$	$132 \pm 31 \pm 5$	4.9σ
$\Xi_c^+(2980) \to \Lambda_c^+ K^- \pi^+$	$152 \pm 37 \pm 45$	4.1σ
$\Xi_c^+(3077) \to \Sigma_c^{++}(2455)K^-$	$87 \pm 20 \pm 4$	5.8σ
$\Xi_c^+(3077) \to \Sigma_c^{++}(2520)K^-$	$82 \pm 23 \pm 6$	4.6σ
$\Xi_c^+(3077) \to \Lambda_c^+ K^- \pi^+$	$35 \pm 24 \pm 1$	1.4σ

$\Xi_c' \rightarrow \Xi_c \gamma$

- State seen by CLEO in 1999 [PRL 82, 492(1999)]
- Seen and studied in $\Xi_c' \rightarrow \Xi_c \gamma$ decay
- Not confirmed since then
- It is lightest state above ground state
- *BABAR* uses both $c\bar{c}$ events and B decays of 232 fb^{-1} of data
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- Details in hep-ex/0607086



$\Xi_c' \rightarrow \Xi_c \gamma$



$\Xi_c' \to \Xi_c \gamma$

- $c\bar{c}$ cross section

  $\sigma(e^+e^- \to \Xi_c'^+ X) \times \mathcal{B}(\Xi_c'^+ \to \Xi^- \pi^+ \pi^+) = 141 \pm 24 \pm 19$ fb

  $\sigma(e^+e^- \to \Xi_c'^0 X) \times \mathcal{B}(\Xi_c'^0 \to \Xi^- \pi^+) = 70 \pm 11 \pm 6$ fb

  $\sigma(e^+e^- \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = 388 \pm 39 \pm 41$ fb

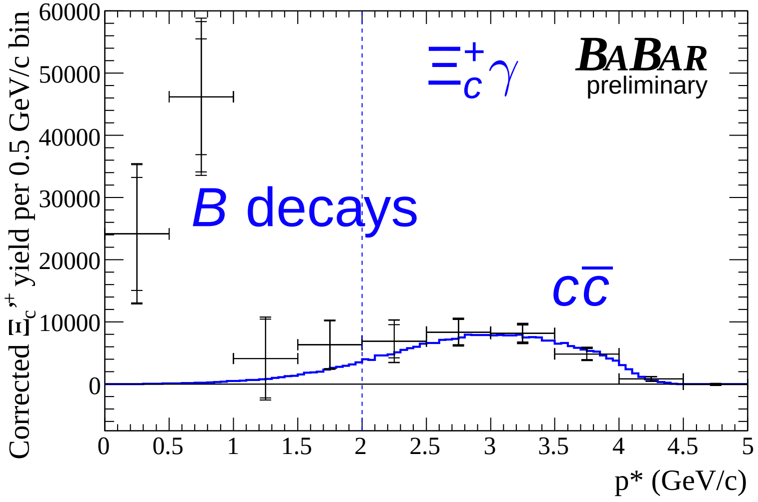
- B production rate

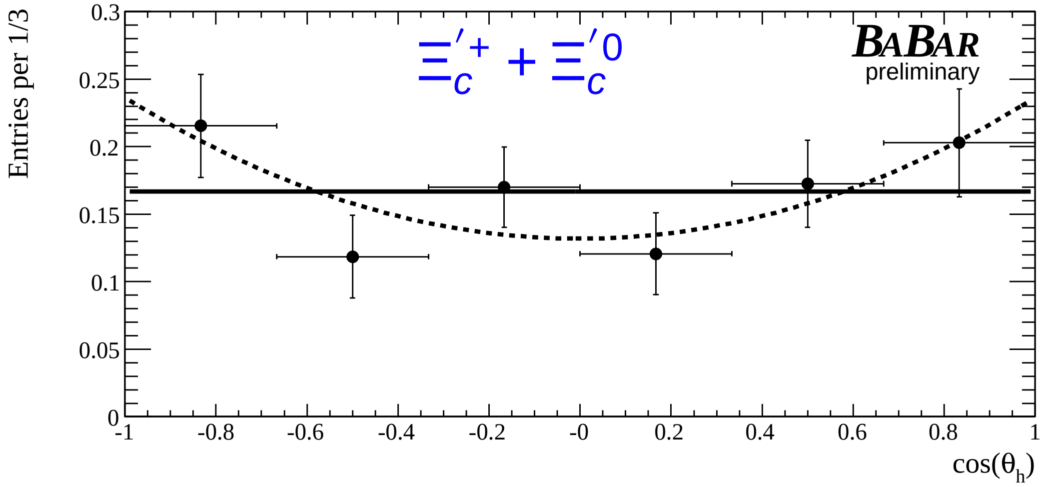
  $\mathcal{B}(B \to \Xi_c'^+ X) \times \mathcal{B}(\Xi_c'^+ \to \Xi^- \pi^+ \pi^+) = (1.69 \pm 0.17 \pm 0.10) \cdot 10^{-4}$

  $\mathcal{B}(B \to \Xi_c'^0 X) \times \mathcal{B}(\Xi_c'^0 \to \Xi^- \pi^+) = (0.67 \pm 0.07 \pm 0.03) \cdot 10^{-4}$

  $\mathcal{B}(B \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (2.11 \pm 0.019 \pm 0.25) \cdot 10^{-4}$

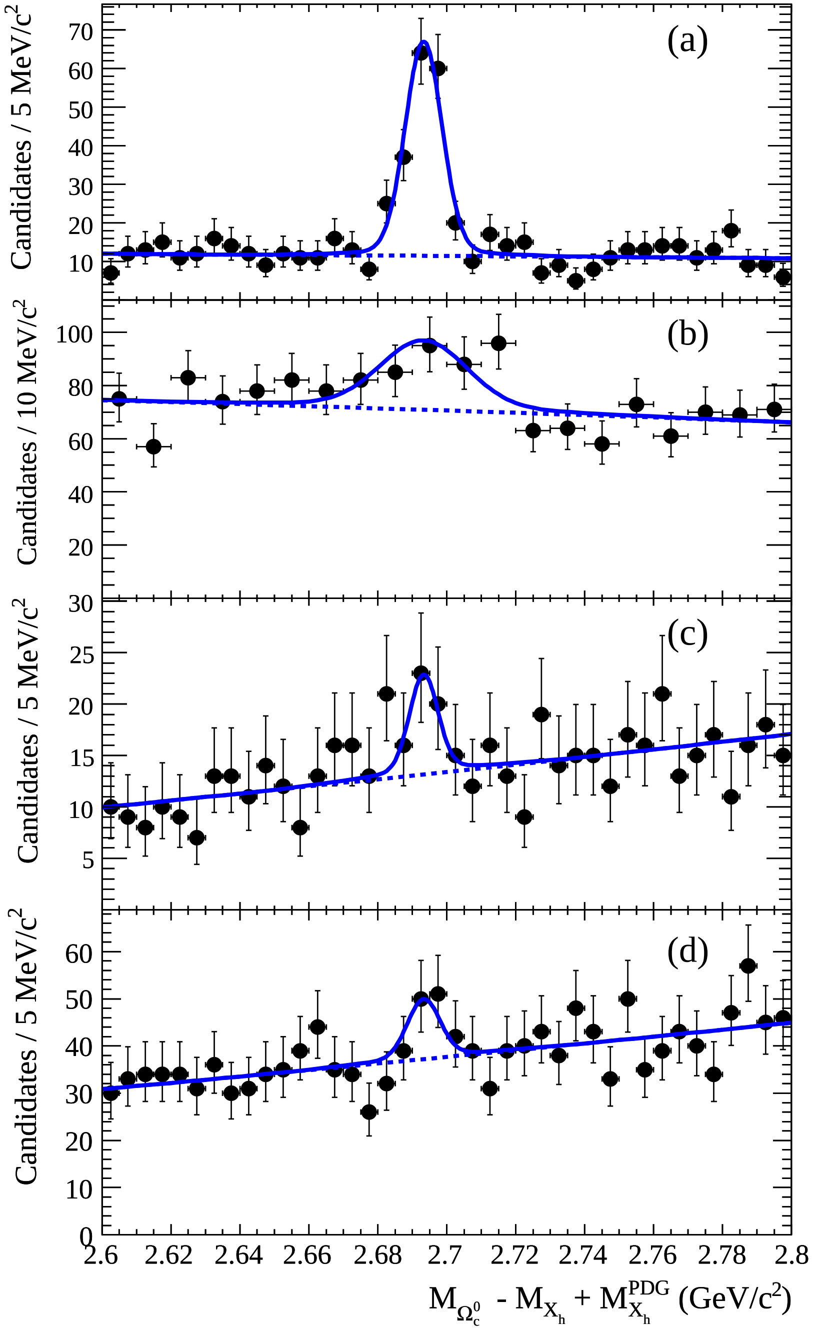
- From helicity angle $J = 1/2$, higher spin cannot be excluded





$\Omega_c^* \to \Omega_c\gamma$

- Ω_c^* last unobserved ground state charm baryon
- *BABAR* search uses 231 fb^{-1} data
- Ω_c reconstructed in channels:
  $\Omega^-\pi^+$; $N = 156 \pm 15$ (a)
  $\Omega^-\pi^+\pi^0$; $N = 92 \pm 26$ (b)
  $\Omega^-\pi^+\pi^-\pi^+$; $N = 23 \pm 10$ (c)
  $\Xi^-K^-\pi^+\pi^+$; $N = 34 \pm 15$ (d)
  $\Omega^- \to \Lambda K^-$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$
- Combine Ω_c with γ



Details in PRL 97, 232001 (2006)

$\Omega_c^* \rightarrow \Omega_c \gamma$

- Use $\Delta M = M_{\Omega_c \gamma} - M_{\Omega_c}$ for better resolution

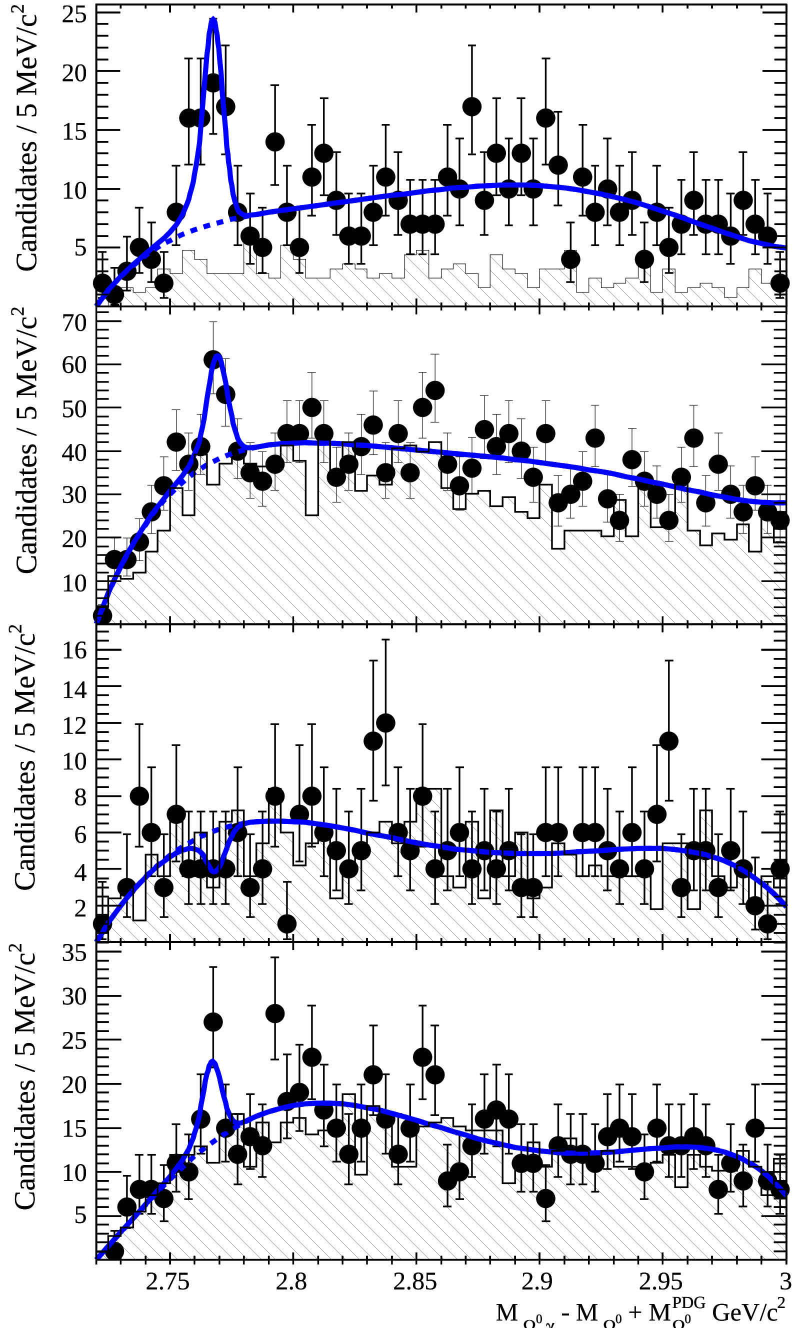
(a) $\Delta M = 69.9 \pm 1.4 \pm 1.0 \mathrm{MeV}/c^2$
$N = 39^{+10}_{-9} \pm 6$; significance 4.2σ

(b) $\Delta M = 71.8 \pm 1.3 \pm 1.1 \mathrm{MeV}/c^2$
$N = 55^{+16}_{-15} \pm 6$; significance 3.4σ

(c) $\Delta M = 69.9 \mathrm{MeV}/c^2$ (fixed)
$N = -5 \pm 5 \pm 1$;

(d) $\Delta M = 69.4^{+1.9}_{-2.0} \pm 1.0 \mathrm{MeV}/c^2$
$N = 20 \pm 9 \pm 3$; significance 2.0σ

$\rightarrow$ Channels consistent
$\Rightarrow$ combine them

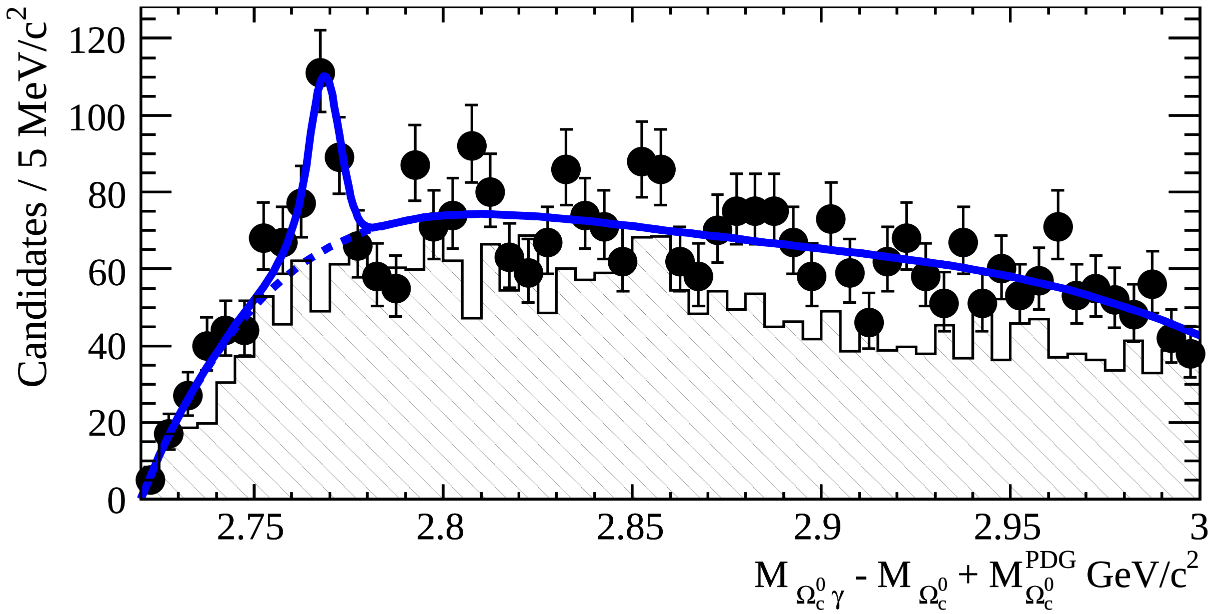


$\Omega_c^* \to \Omega_c \gamma$

- Fit with Crystal ball function for signal with fixed shape parameters
- $\Delta M = 70.8 \pm 1.0 \pm 1.1\,\mathrm{MeV}/c^2$
- $N = 105 \pm 21 \pm 6$
- 5.2σ significance

Predictions for ΔM (MeV/c^2)

- HQET 80
- Lattice QCD 90
- Non-relativistic Quark Model 50-73



Σ_b expectations

- Up to now Λ_b only directly observed *b*-baryon
- Lack of the experimental result mainly due to the statistics
- Tevatron experiments start to have enough statistics to search for other *b*-baryons
- Decay via p-wave π

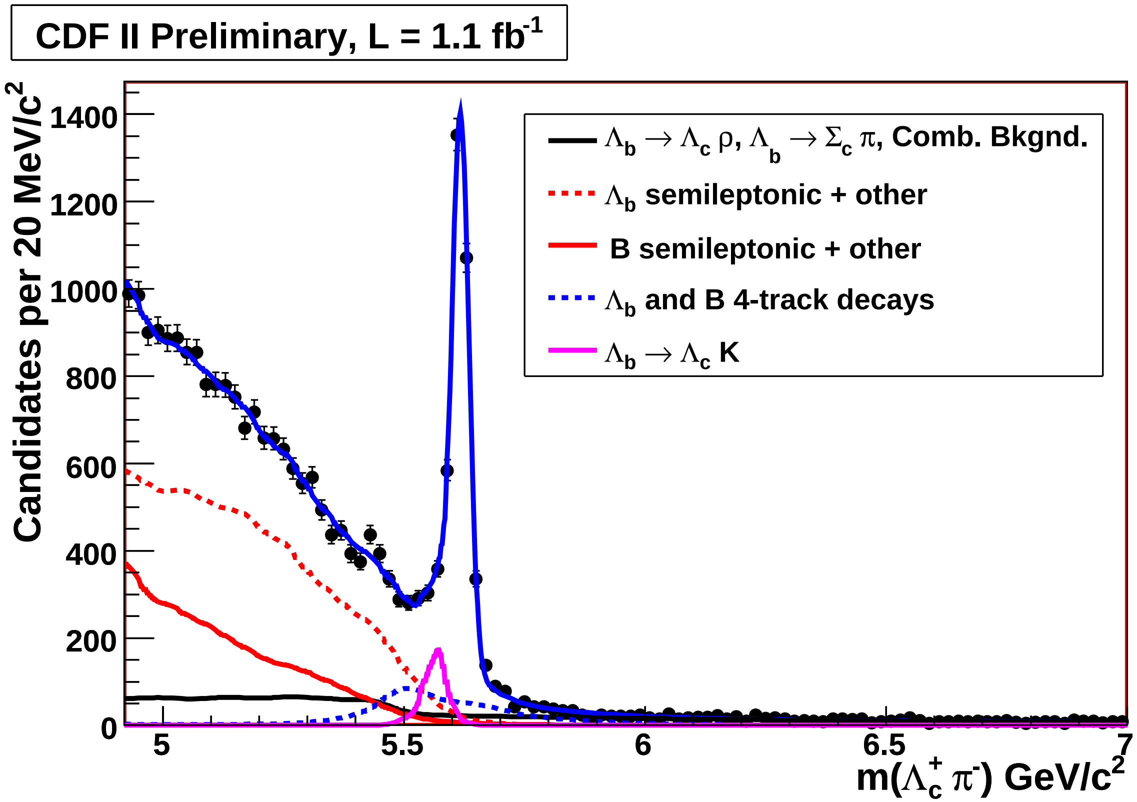
$$\Sigma_b\text{: } bqq \qquad J^P = S_Q + s_{qq} \quad \begin{array}{l} \rightarrow 3/2^+ \ (\Sigma_b^*) \\ \rightarrow 1/2^+ \ (\Sigma_b) \end{array}$$

$\Sigma_b^{(*)+}$	uub
$\Sigma_b^{(*)-}$	ddb
$\Sigma_b^{(*)0}$	udb

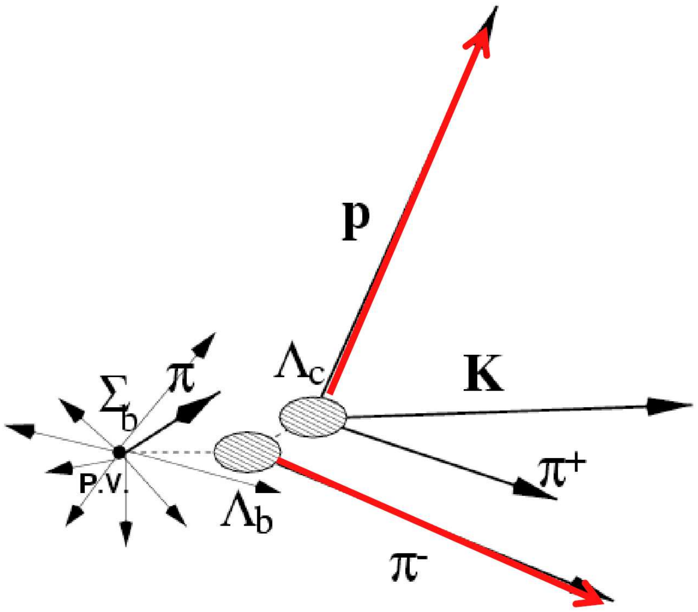
$\Sigma_b^{(*)0}$ decays through π^0, can't be seen at CDF

Property	Expectation (MeV$/c^2$)
$m(\Sigma_b) - m(\Lambda_b)$	180 — 210
$m(\Sigma_b^*) - m(\Sigma_b)$	10 — 40
$m(\Sigma_b^-) - m(\Sigma_b^+)$	5 — 7
$\Gamma(\Sigma_b)$, $\Gamma(\Sigma_b^*)$	≈ 8, ≈ 15

Λ_b and sample composition



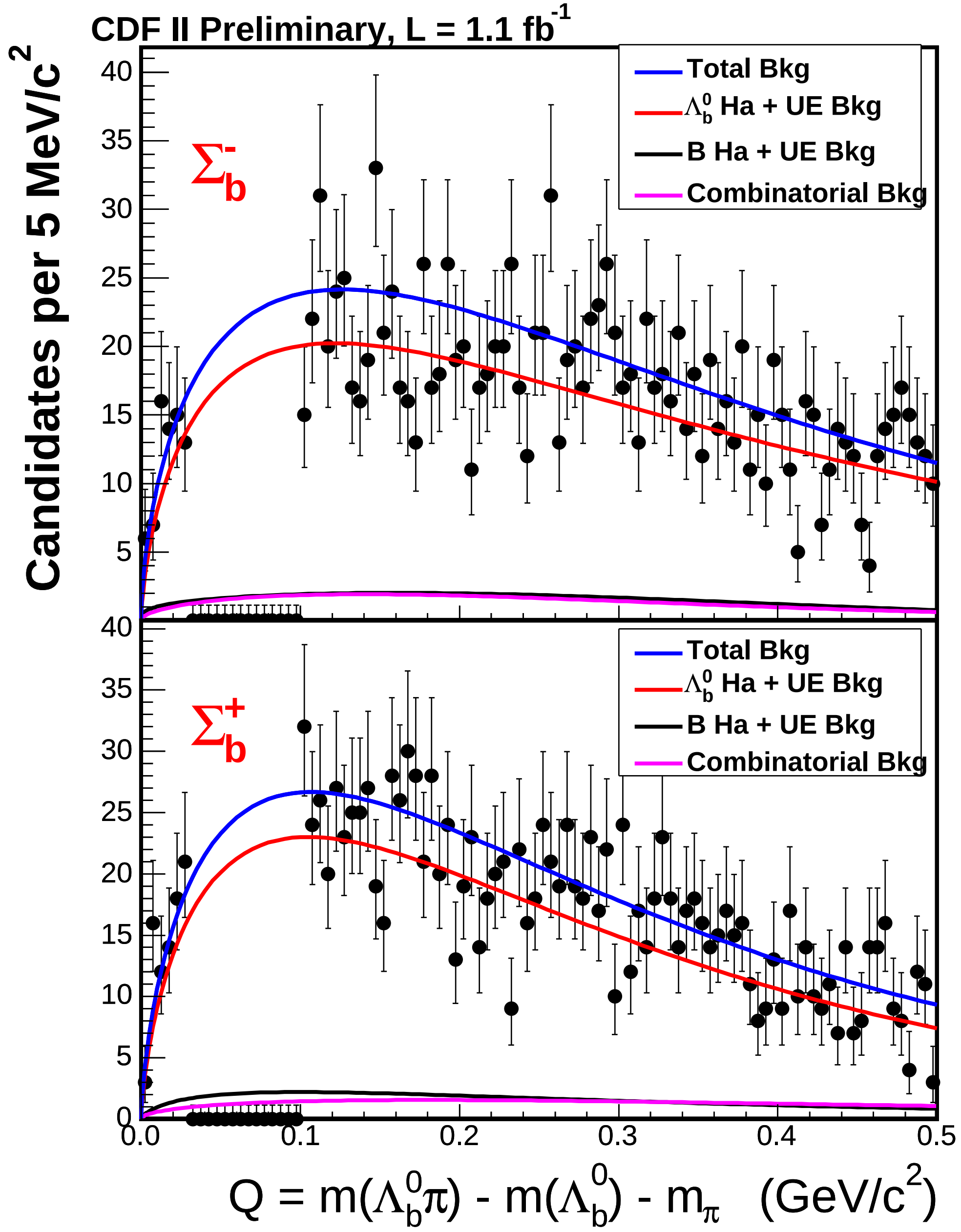
- $\Lambda_b \rightarrow \Lambda_c^+\pi^-$, $\Lambda_c^+ \rightarrow pK^-\pi^+$
- With 1.1 fb^{-1} around 3000 Λ_b $\Rightarrow$ worlds largest sample
- For Σ_b search select narrow region around fully reconstructed peak



Λ_b	86%
B mesons	10%
combinatorial	4%

Background estimation

- Do blind search
- Fix all backgrounds before looking to signal region
- Shapes
  Λ_b sideband
  PYTHIA MC
  B miss-reconstructed data
- Relative normalization according to Λ_b mass fit
- Determined background describes data well

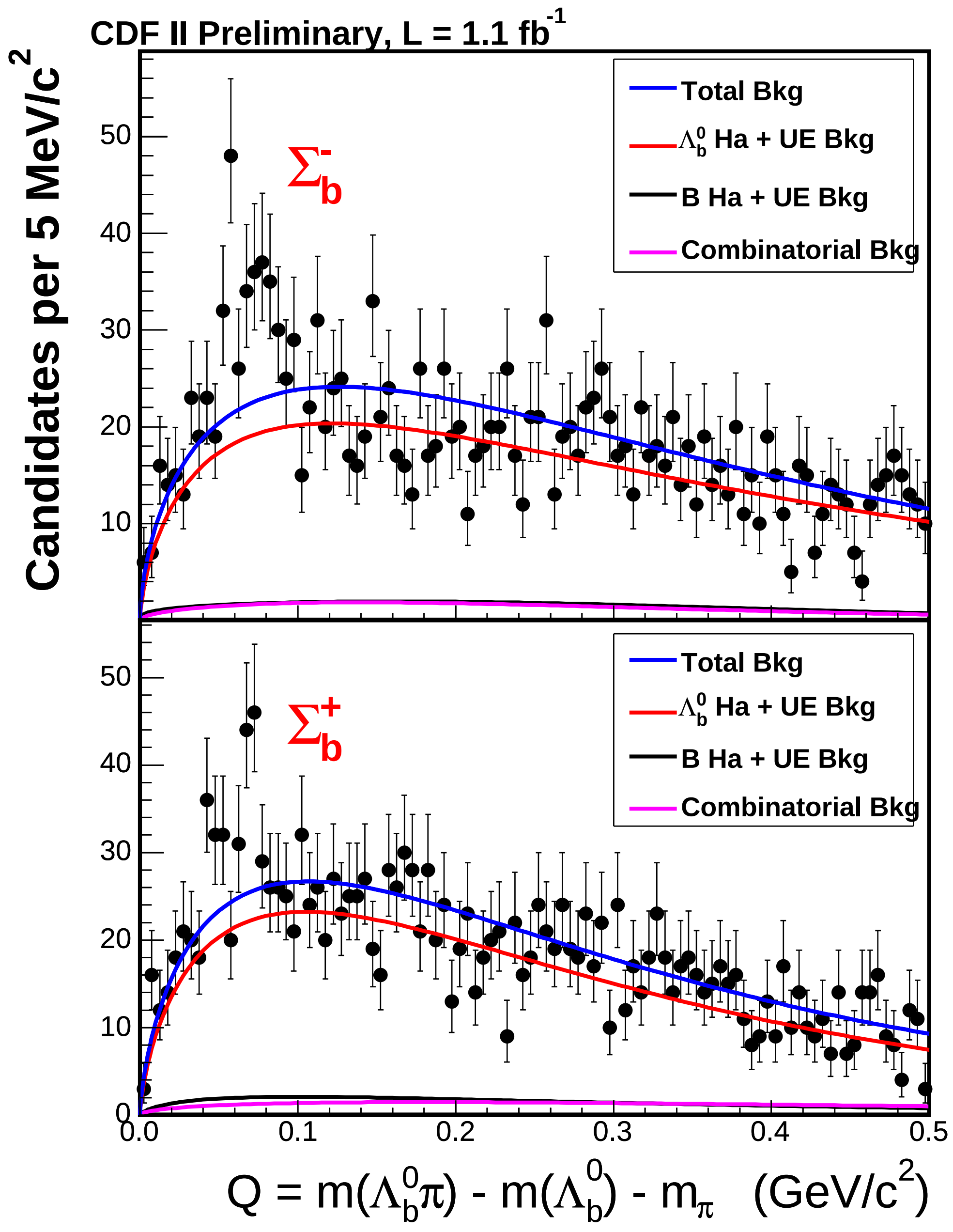


Unblinded Σ_b Q-distribution

- Excess after unblinding

	Data	bkg	excess
$\Sigma_b^{(*)-}$	416	268	148
$\Sigma_b^{(*)+}$	406	298	108

- Data indicate two peaks for each charge
- Do unbinned maximum likelihood fit
- Fit for Q values and number of events



Σ_b Fit result

- Mass differences (MeV/c^2)

$\rightarrow$ $m(\Sigma_b^-) - m(\Lambda_b) - m(\pi) =$
$55.9 \pm 1.0(\mathrm{stat}) \pm 0.1(\mathrm{sys})$

$\rightarrow$ $m(\Sigma_b^+) - m(\Lambda_b) - m(\pi) =$
$48.4^{+2.0}_{-2.3}(\mathrm{stat}) \pm 0.1(\mathrm{sys})$

$\rightarrow$ $m(\Sigma_b^*) - m(\Sigma_b) =$
$21.3^{+2.0}_{-1.9}(\mathrm{stat})^{+0.4}_{-0.2}(\mathrm{sys})$

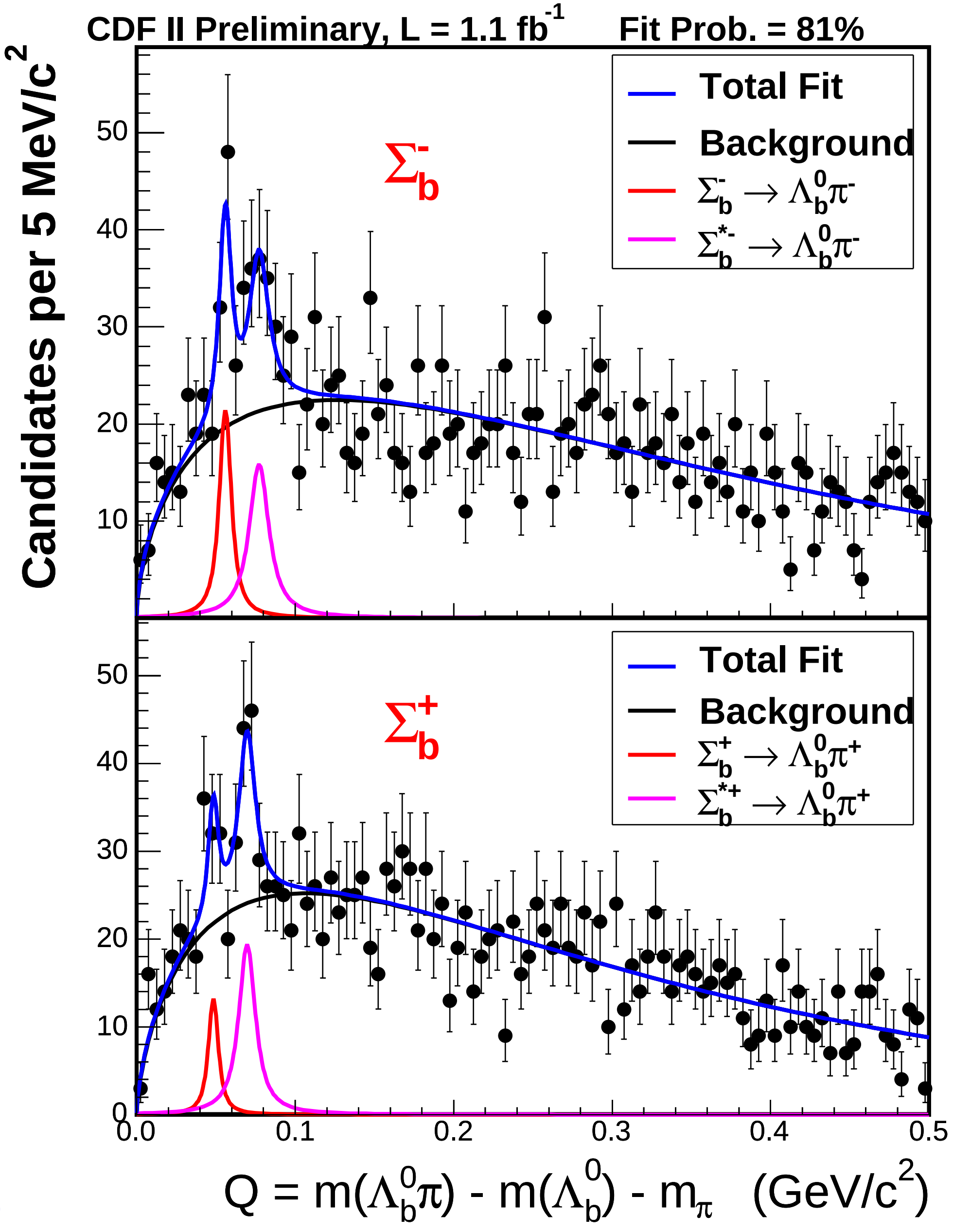
- Signal events

$\rightarrow$ $N(\Sigma_b^+) = 29^{+12.4}_{-11.6}(\mathrm{stat})^{+5.0}_{-3.4}(\mathrm{sys})$

$\rightarrow$ $N(\Sigma_b^-) = 60^{+14.8}_{-13.8}(\mathrm{stat})^{+8.4}_{-4.0}(\mathrm{sys})$

$\rightarrow$ $N(\Sigma_b^{*+}) = 74^{+17.2}_{-16.3}(\mathrm{stat})^{+10.3}_{-5.7}(\mathrm{sys})$

$\rightarrow$ $N(\Sigma_b^{*-}) = 74^{+18.2}_{-17.4}(\mathrm{stat})^{+15.6}_{-5.0}(\mathrm{sys})$



Σ_b Significance

- Repeat fit with alternative hypothesis
  - Single peak left out
  - Only one peak in each charge combination
  - No peak, pure background
- Derived from $\Delta(-\ln\mathcal{L})$

Hypothesis	$\Delta(-\ln\mathcal{L})$	Hypothesis	$\Delta(-\ln\mathcal{L})$
Null	44.7	No Σ_b^-	10.4
2 peaks	14.3	No Σ_b^+	1.1
		No Σ_b^{*-}	10.1
		No Σ_b^{*+}	9.8

$\Rightarrow$ Significance more than 5σ for 4 peaks

$\Rightarrow$ Evidence for three out of four individual peaks

Details at
http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-sigmab

Conclusions

- Last year very rich for Heavy Quark Baryons
- Several new baryon states in charm sector discovered
  $\Lambda_c^+(2940)$, $\Xi_c^{+,0}(2980)$, $\Xi_c^{+,0}(3077)$ and Ω_c^*
- Several refined measurements in charm sector
- Charged Σ_b states discovered in bottom sector

$\Rightarrow$ Our knowledge about Heavy Quark Baryons increased

$\longrightarrow$ I'm convinced this was not our last word on the topic