CHARM SPECTROSCOPY AT BABAR

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On behalf of the BaBar collaboration

XII. INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY

8-13 OCTOBER 2007

Laboratori Nazionali di Frascati (Rome)

CHARM SPECTROSCOPY AT BABAR

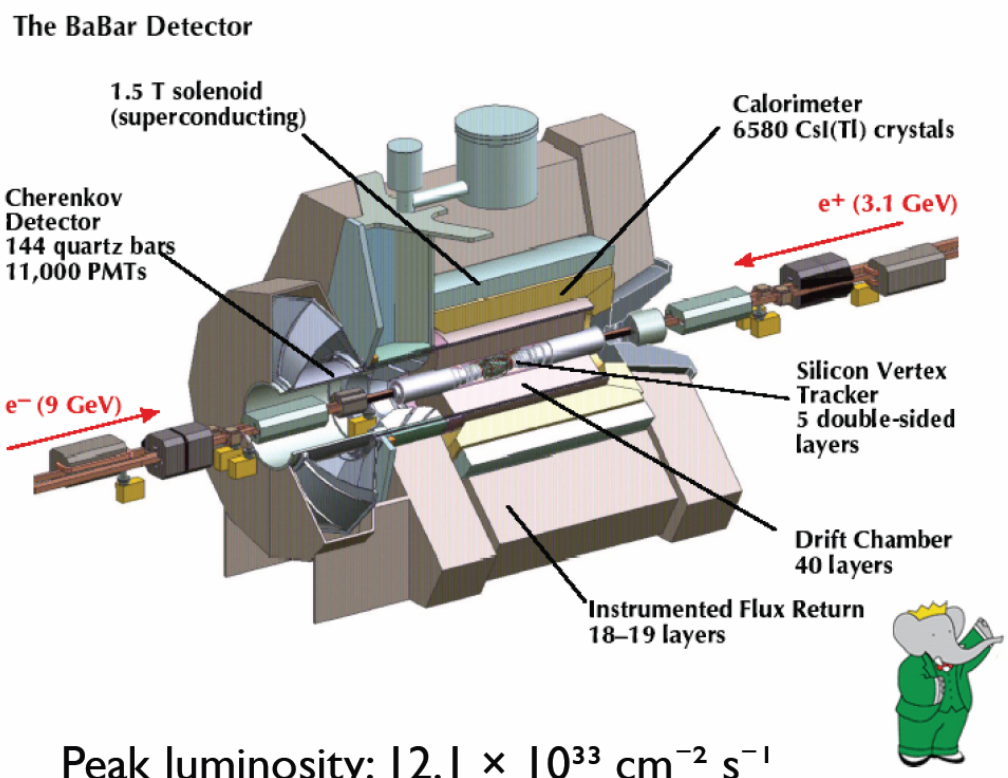
- $c\bar{s}$ mesons
  - **$D_{s1}(2536)$**: precise measurements
  - **$D_{s0}^*(2317)$** and **$D_{s1}(2460)$**: the first surprises
  - **$D_{sJ}^*(2860)$**: one more surprise
  - **X(2690)** and **$D_{sJ}(2700)$**: last surprises?

- Charmed baryons
  - Observation of Ω_c^0 and discovery of Ω_c^{*0}
  - Discovery of $\Lambda_c(2940)$
  - Observation of $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$
  - Discovery of $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$

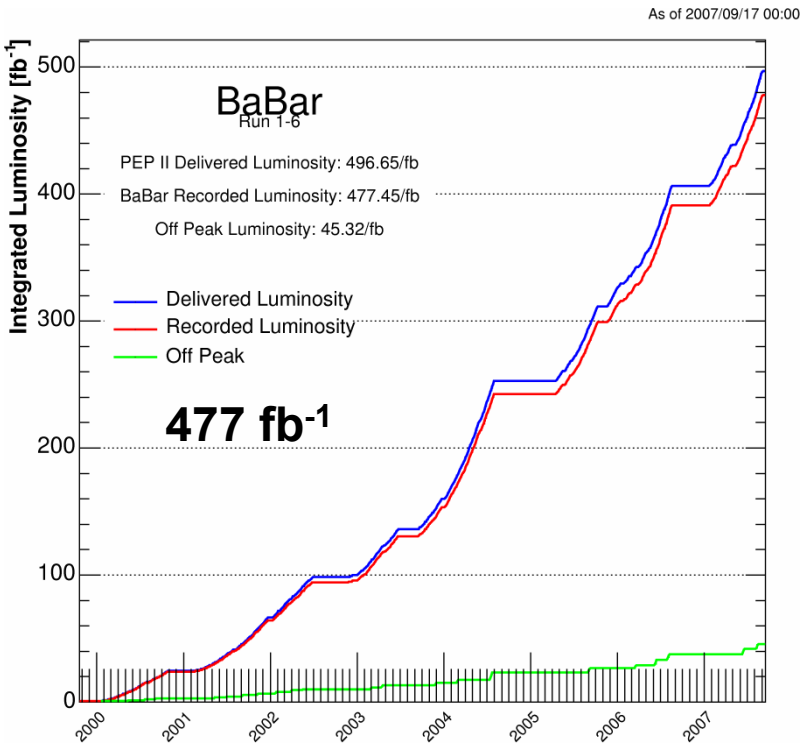
- Not mentioned in this talk
  - D, D* mesons

- Charmonium spectroscopy in BaBar is covered by Arafat Mokhtar
  - Talk given on Monday at 14h00, in the session "**Quarkonia states**"

BABAR: B AND c-FACTORIES



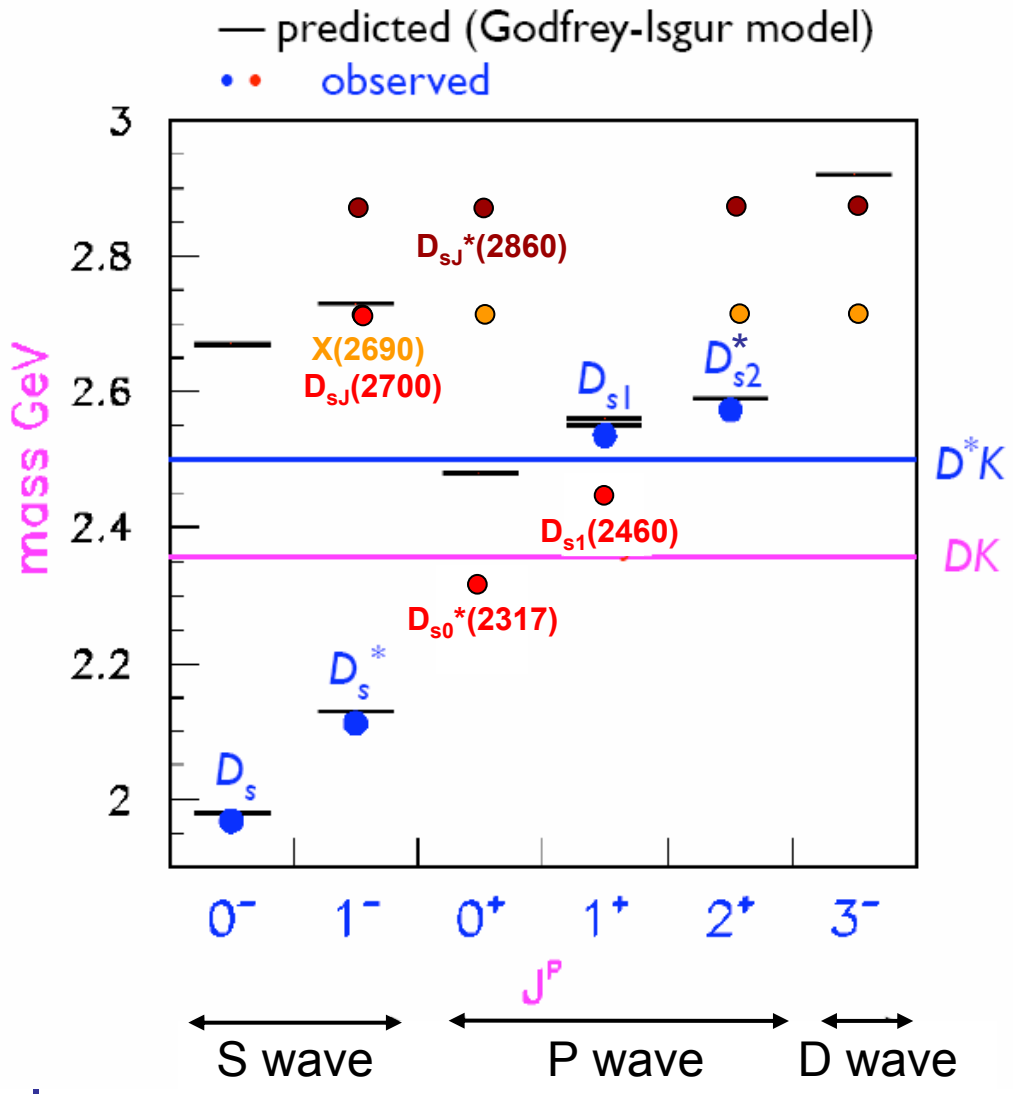
Peak luminosity: 12.1 × 10^{33} cm^{-2} s^{-1}



$c\bar{s}$ MESONS

WHAT IS NEW FOR D_{sJ} STATES?

CURRENT SITUATION

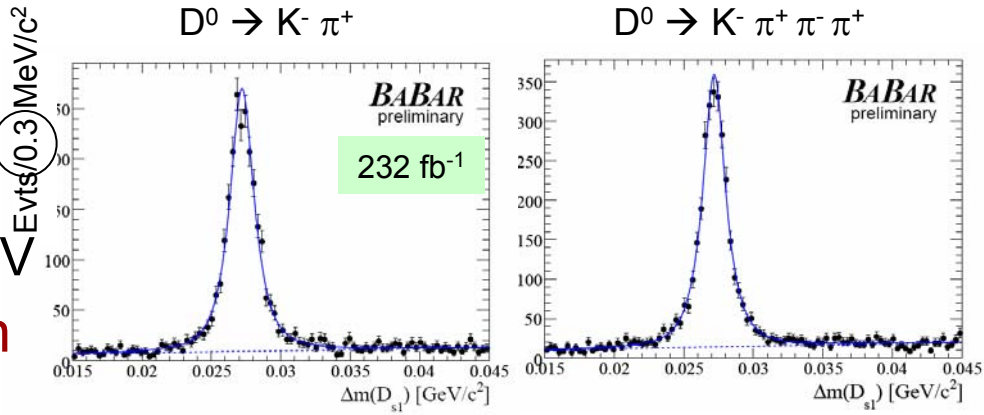


- D_s^*, $D_{s1}(2536)^+$, $D_{s2}(2573)^+$: well known, but J^P only **inferred** (not measured!)
- $D_{s0}^*(2317)^+$, Apr. 2003: unexpected observation of a narrow resonance in **BaBar**
- $D_{s1}(2460)^+$, May 2003: **CLEO, BaBar** observed a new narrow resonance
- $D_{sJ}^*(2860)^+$, Jul. 2006: new state discovered by **BaBar**
- $X(2690)^+$, Jul. 2006: broad enhancement seen in **BaBar**
- $D_{sJ}(2700)^+$, Jul. 2006: new state discovered by **Belle** (≡ X(2690)?)

Let's go step by step!

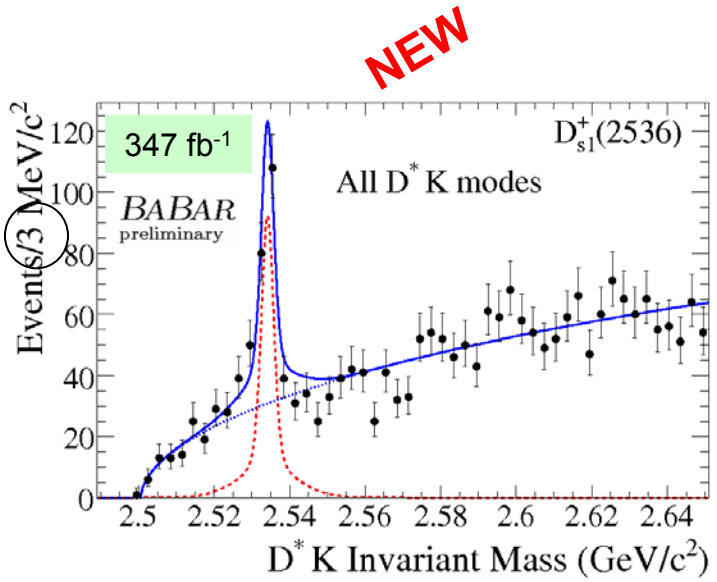
$D_{s1}(2536)$: NEW RESULTS

- High precision measurement of $D_{s1} \rightarrow D^{*+}K^0_s$ in continuum
- Mass
  - M = 2534.85 ± 0.02 ± 0.40 MeV
- First measurement of the width
  - Γ = 1.03 ± 0.05 ± 0.12 MeV



$p^* > 2.7$ GeV/c $\Delta m(D_{s1}) = m(D_{s1}) - m(D^*) - m(K^0_s)$

- First observation of D_{s1} in B decays
  - $B \rightarrow D^{(*)}D_{s1}$ (8 modes), $D_{s1} \rightarrow D^*K$
  - N = 182 ± 19 events, 12σ
- Mass
  - M = 2534.78 ± 0.31 ± 0.40 MeV
- J^P quantum number
  - Statistics **too low** to conclude yet



BaBar: hep-ex/0607084
BaBar: hep-ex/0708.1565

$D_{s0}^*(2317)$ AND $D_{s1}(2460)$ UPDATE

- Discovered 4 years ago in $e^+e^- \to c\bar{c}$ events ; subsequently observed in B decays

- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ very well established and known experimentally
  - **Masses** and tight upper limits on **widths**
  - **J^P**: 0^+ for $D_{s0}^*(2317)$ and 1^+ for $D_{s1}(2460)$
  - **decay modes** and **branching fractions**

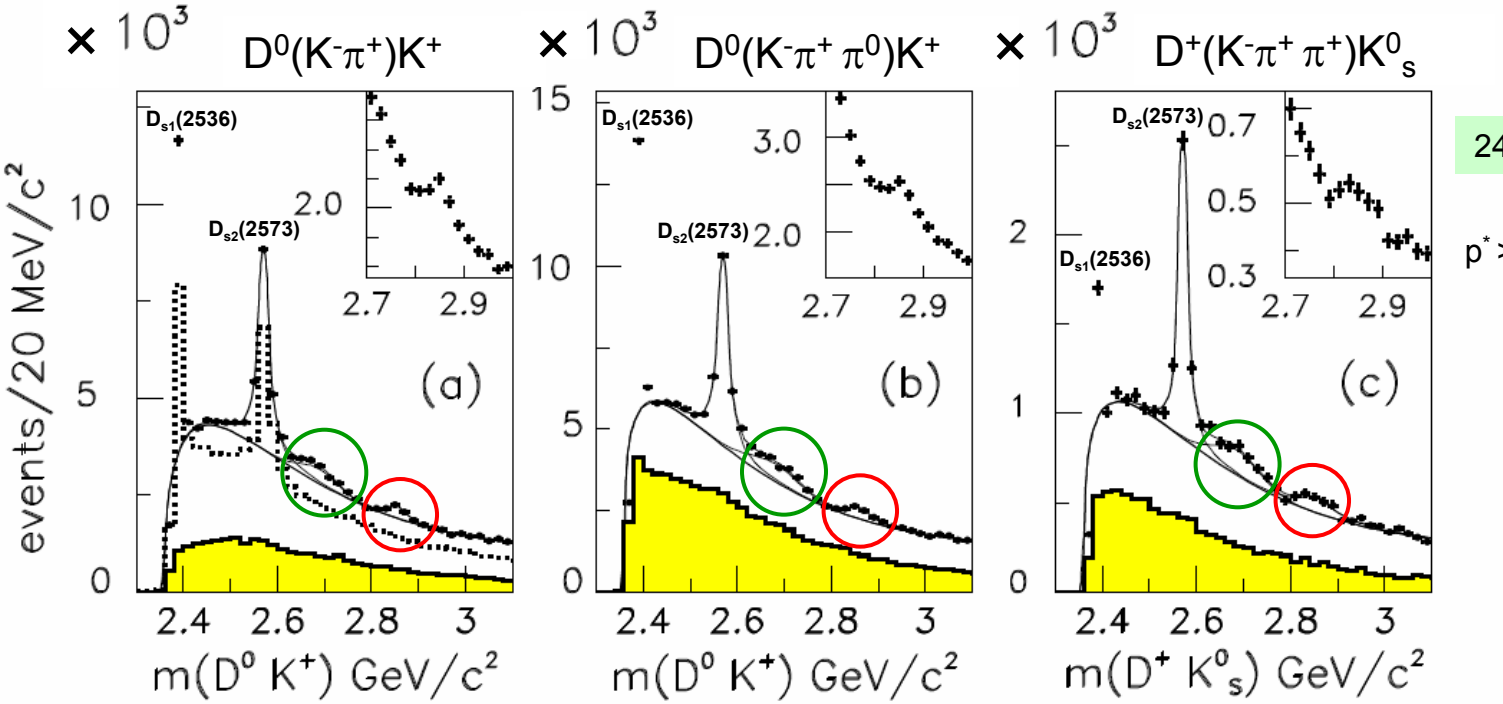
- Interpretation of these new states still unclear!
  - One possibility: identify these 2 states as the **0^+ and 1^+ $c\bar{s}$ states**
    - However strong difficulties within the potential model
  - **Other** possibilities
    - 4 quark states? DK molecule? $D\pi$ atom? Chiral symmetry?

- Are there some more suprises? Yes!

Belle: Phys. Rev. Lett. 91 (2003) 262001
BaBar: Phys. Rev. D74 (2006) 032007
Belle: Belle-Conf-0461 (2006)
BaBar: Phys. Rev. D74 (2006) 031103

D_{sJ}*(2860): ANOTHER NEW STATE

- Looking in the $c\bar{c}$ continuum: $e^+e^- \to D^0(K^-\pi^+, K^-\pi^+\pi^0)K^+X$ and $e^+e^- \to D^+(K^-\pi^+\pi^+)K^0_sX$

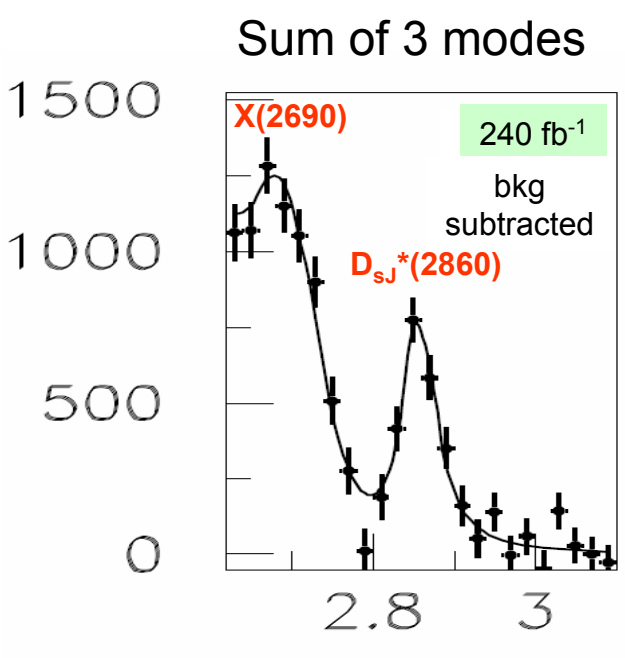


- ◯ New state at 2860 MeV/c^2! (fit with a Breit-Wigner)
- ◯ Bump at 2690 MeV/c^2? (better fit with a Gaussian than a Breit-Wigner)

BaBar: Phys. Rev. Lett. 97 (2006) 222001

D_{sJ}*(2860) AND… X(2690)?

- Combining the 3 modes
  - M = (2856.6 ± 1.5 ± 5.0) MeV/c^2
  - Γ = (47 ± 7 ± 10) MeV
  - J^P = **0^+, 1^-, 2^+**, …
    - Final state is DK, i.e. two pseudoscalars
- Interpretation of D_{sJ}*(2860)?
  - **Radial excitation** of D_{s0}*(2317)? hep-ph/0606110
  - $c\bar{s}$ with J^P = **3^-**? hep-ph/0607245
  - $c\bar{s}$ with J^P = **0^+**? hep-ph/0608139



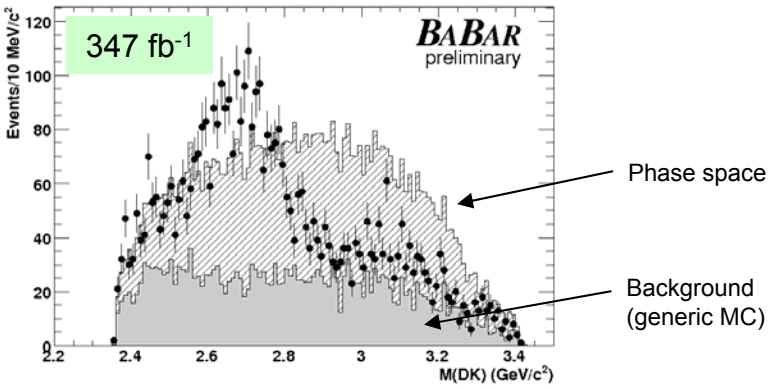
- Another structure at 2690 MeV/c^2?
  - M = (2688 ± 4 ± 3) MeV/c^2
  - Γ = (112 ± 7 ± 36) MeV
- Need confirmation by other experiments or in other channels…

BaBar: Phys. Rev. Lett. 97 (2006) 222001

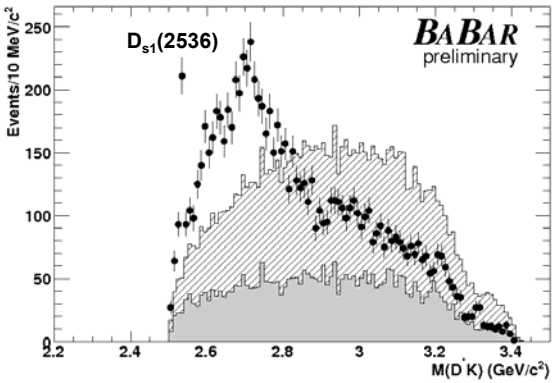
EVEN MORE STATES: $D_{sJ}(2700)$

- New resonance decaying to D^0K^+ discovered by Belle in $B^+ \to \bar{D}^0(D^0K^+)$
  - **$D_{sJ}(2700)$**
- Same resonance as seen by BaBar in continuum, X(2690)?
  - Mass and width consistent, same decay mode
- Study of $B \to \bar{D}^{(*)}D^{(*)}K$ decays in BaBar
  - Looking at 8 DK + 8 D*K invariant masses

Summing all 8 DK modes



Summing all 8 D*K modes



- Enhancement observed around 2700 MeV/c^2 in DK and D*K
- Full Dalitz plot analysis ongoing

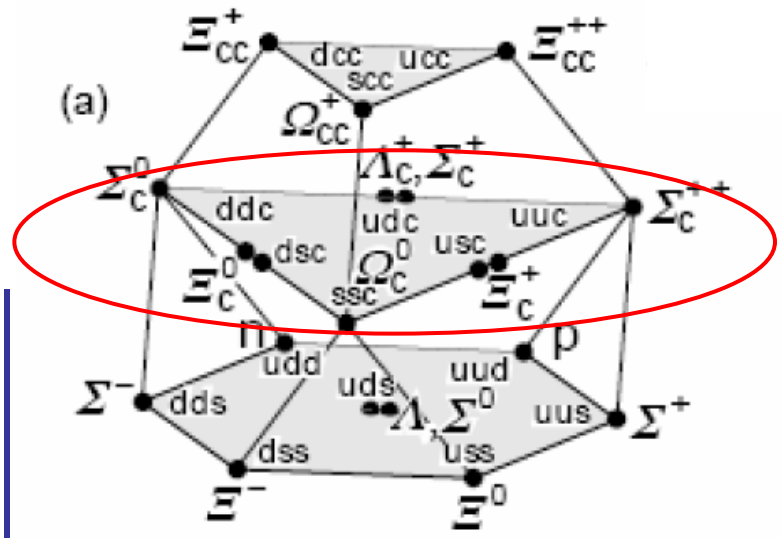
BaBar: preliminary

CHARMED BARYONS

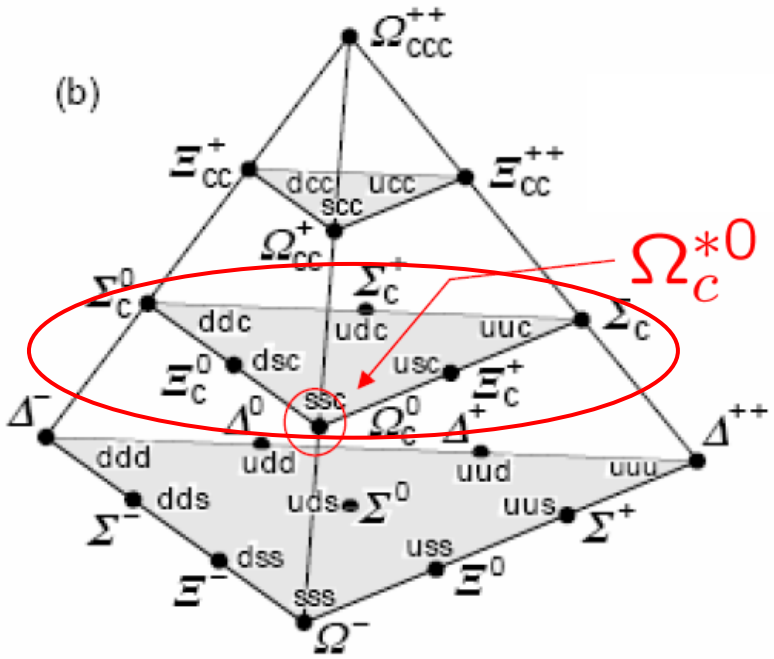
CURRENT STATE

- All 9 ground states with $J^P=1/2^+$ observed
- 5 out of 6 ground states with $J^P=3/2^+$ observed
  - only Ω_c^{*0} was missing

$J^P = 1/2^+$



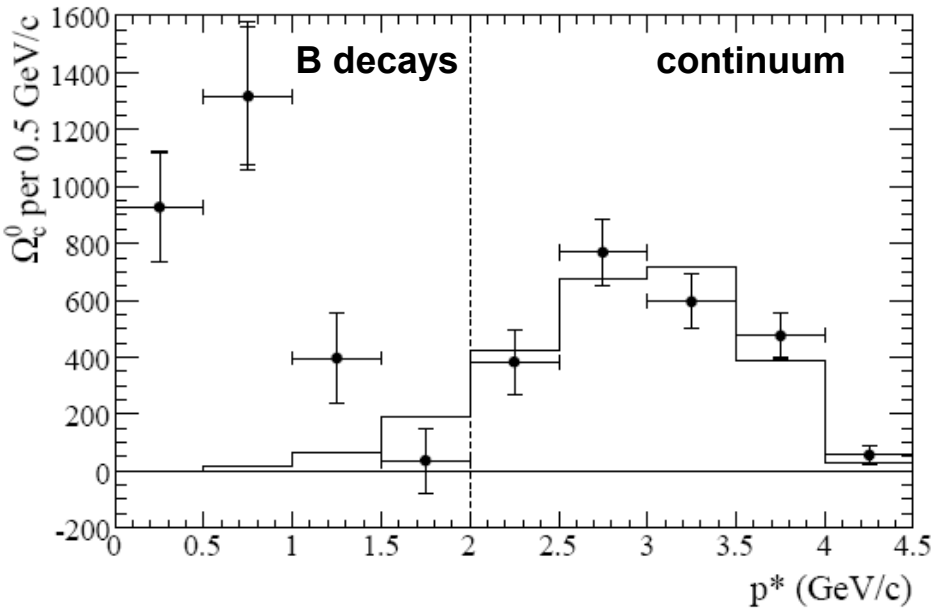
$J^P = 3/2^+$

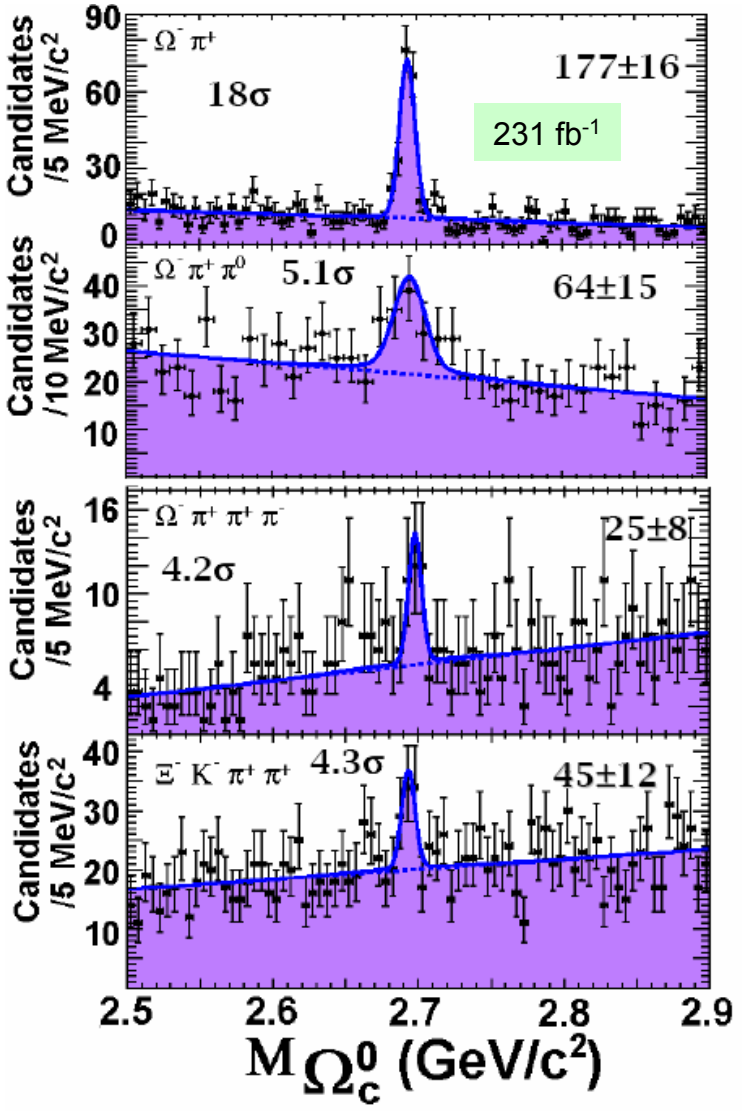


STUDY OF Ω_c^0

NEW

- Ω_c^0: css charm baryon ground state
- Observed in 4 modes
- First observation of B → Ω_c^0 X





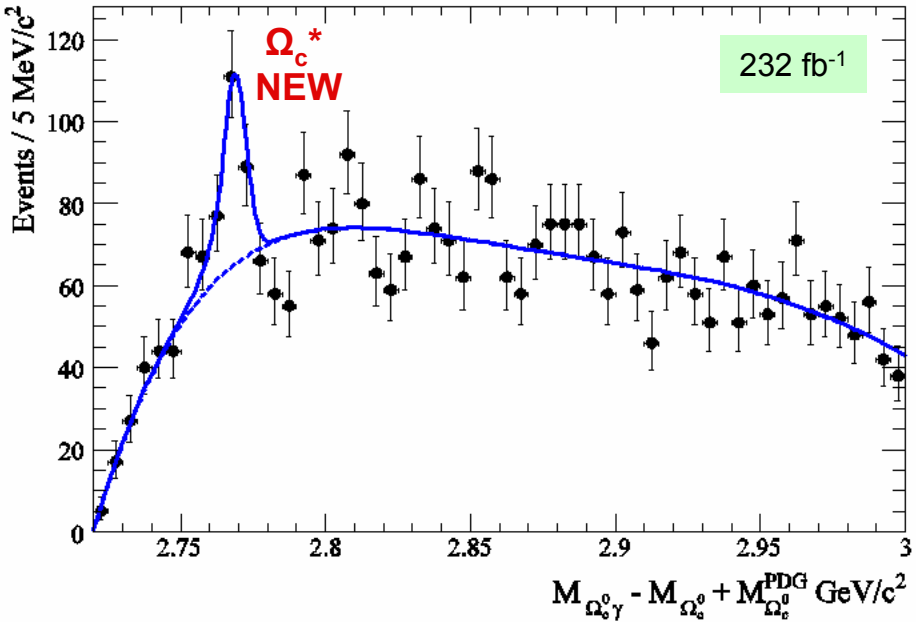
- $B(B \to \Omega_c^0 X) \times B(\Omega_c^0 \to \Omega^- \pi^+)$
  $= (5.2 \pm 0.9 \pm 0.5) \times 10^{-6}$

BaBar: Phys. Rev. Lett. 99 (2007) 062001

DISCOVERY OF Ω_c^{*0}

- $\Omega_c^{*0} \rightarrow \Omega_c^0 \gamma$, in e+e- $\rightarrow \Omega_c^{*0} X$
  - css baryon, $J^P = 3/2^+$
- Combining 4 decay modes of Ω_c^0 gives
  - 105 ± 21 ± 6 events
  - 5.2σ significance
- Difference of mass $\Delta m = m(\Omega_c^{*0}) - m(\Omega_c^0)$
  - Measured: **70.8 ± 1.0 ± 1.1 MeV/c²**
  - Predicted range: 50 – 94 MeV/c²
- Branching fraction ratio:

$$\frac{\sigma(e^+e^- \rightarrow \Omega_c^{*0} X, x_p(\Omega_c^{*0}) > 0.5)}{\sigma(e^+e^- \rightarrow \Omega_c^0 X, x_p(\Omega_c^0) > 0.5)} = 1.01 \pm 0.23 \pm 0.11$$



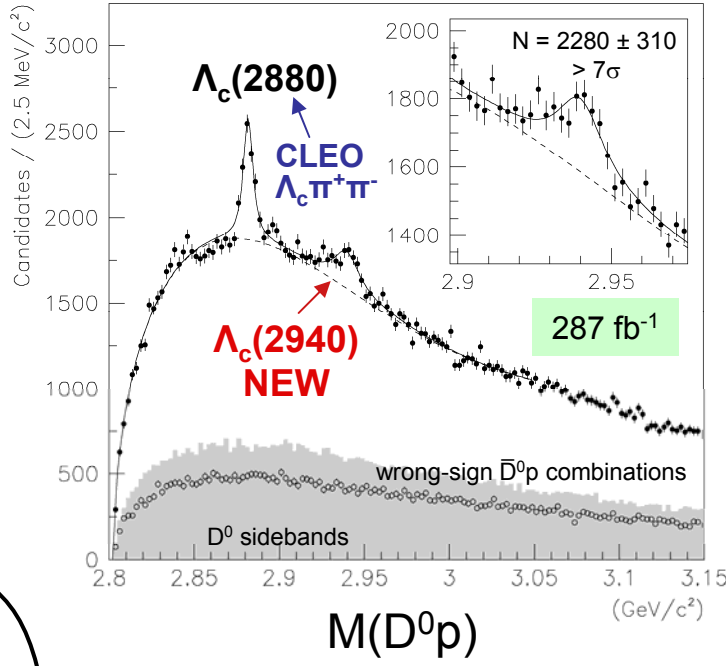
- $\Omega_c^0 \rightarrow \Omega^-\pi^+,\ \Omega^- \rightarrow \Lambda K^-$
- $\Omega_c^0 \rightarrow \Omega^-\pi^+\pi^0,\ \Omega^- \rightarrow \Lambda K^-$
- $\Omega_c^0 \rightarrow \Omega^-\pi^+\pi^-\pi^+,\ \Omega^- \rightarrow \Lambda K^-$
- $\Omega_c^0 \rightarrow \Xi^- K^-\pi^+\pi^+,\ \Xi^- \rightarrow \Lambda\pi^-$

BaBar: Phys. Rev. Lett. 97 (2006) 232001

DISCOVERY OF $\Lambda_c(2940)$

- New baryon: $\Lambda_c(2940) \rightarrow D^0p$
  - **First observation** of charmed baryons decaying to D meson and light baryon
  - Simplest explanation: **udc** baryon
- Measurements of M and Γ are consistent

	M, MeV/c^2	Γ, MeV
BaBar $\Lambda_c(2940)^+$	$2939.8 \pm 1.3 \pm 1.0$	$17.5 \pm 5.2 \pm 5.9$
Belle $\Lambda_c(2940)^+$	$2938.0 \pm 1.3^{+2.0}_{-4.0}$	$13^{+8}_{-5}{}^{+27}_{-7}$
CLEO $\Lambda_c(2880)^+$	$2882 \pm 1 \pm 2$	$4 \pm 2 \pm 2$
BaBar $\Lambda_c(2880)^+$	$2881.9 \pm 0.1 \pm 0.5$	$5.8 \pm 1.5 \pm 1.1$
Belle $\Lambda_c(2880)^+$	$2881.2 \pm 0.2 \pm 0.4$	$5.8 \pm 0.7 \pm 1.1$



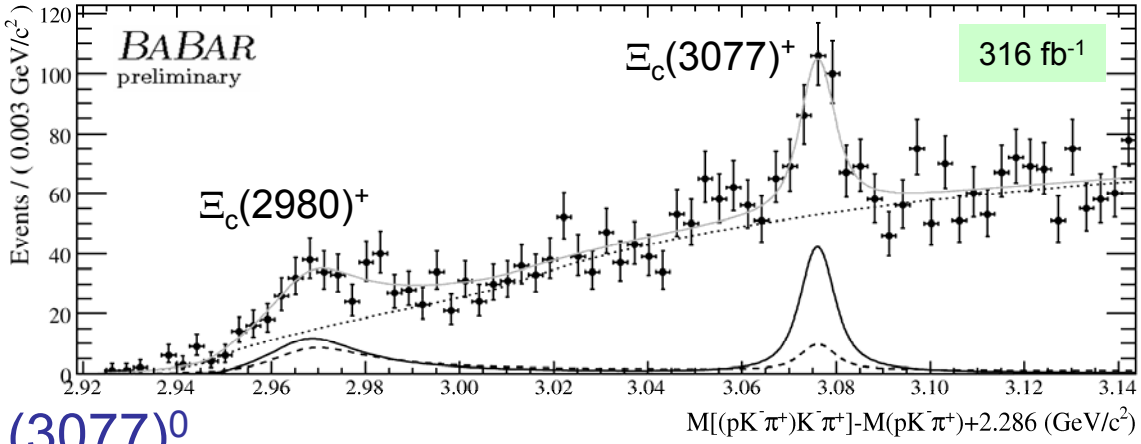
Confirmed later by Belle in $\Lambda_c^+\pi^+\pi^-$

- No signals in D^+p for both baryons
  - Isospin = 0
  - Both states are isoscalars (Λ_c not Σ_c)

BaBar: Phys. Rev. Lett. 98 (2007) 012001

OBSERVATION OF $\Xi_c(2980)^+$ AND $\Xi_c(3077)^+$

- $\Xi_c(2980)^+$, $\Xi_c(3077)^+$ and $\Xi_c(3077)^0$ first observed by Belle
  - Excited **charm-strange** baryons
- Confirmed by BaBar in $\Lambda_c^+ K^- \pi^+$, with $\Lambda_c^+ \to p\, K^-\, \pi^+$



- BaBar confirmed also $\Xi_c(3077)^0$
- Comparison of M and Γ measurements

	M, MeV/c^2	Γ, MeV
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 $\Xi_c(3080)^+$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$
BaBar $\Xi_c(3080)^+$	$3076.4 \pm 0.7 \pm 0.3$	$6.2 \pm 1.6 \pm 0.5$
Belle $\Xi_c(3080)^0$	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$
BaBar $\Xi_c(3080)^0$	$3079.3 \pm 1.1 \pm 0.2$	$5.9 \pm 2.3 \pm 1.5$

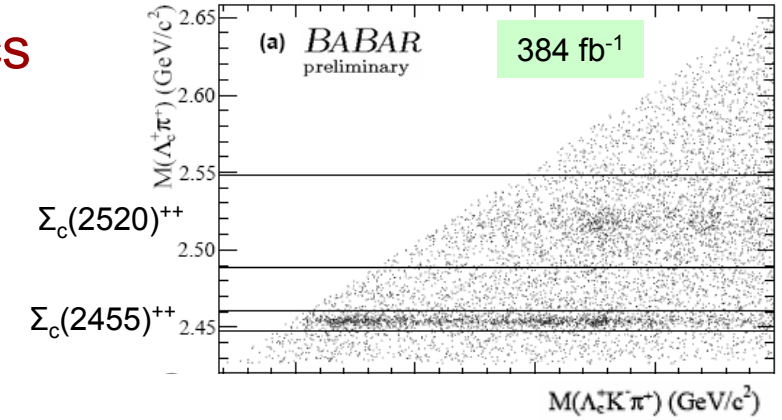
Different: BaBar incorporates phase space effects near threshold and decay to Σ_c^{++} K^-

Good agreement

BaBar: hep-ex/0607042

DISCOVERY OF $\Xi_c(3055)^+$ AND $\Xi_c(3123)^+$ NEW

- Updated analysis with more statistics

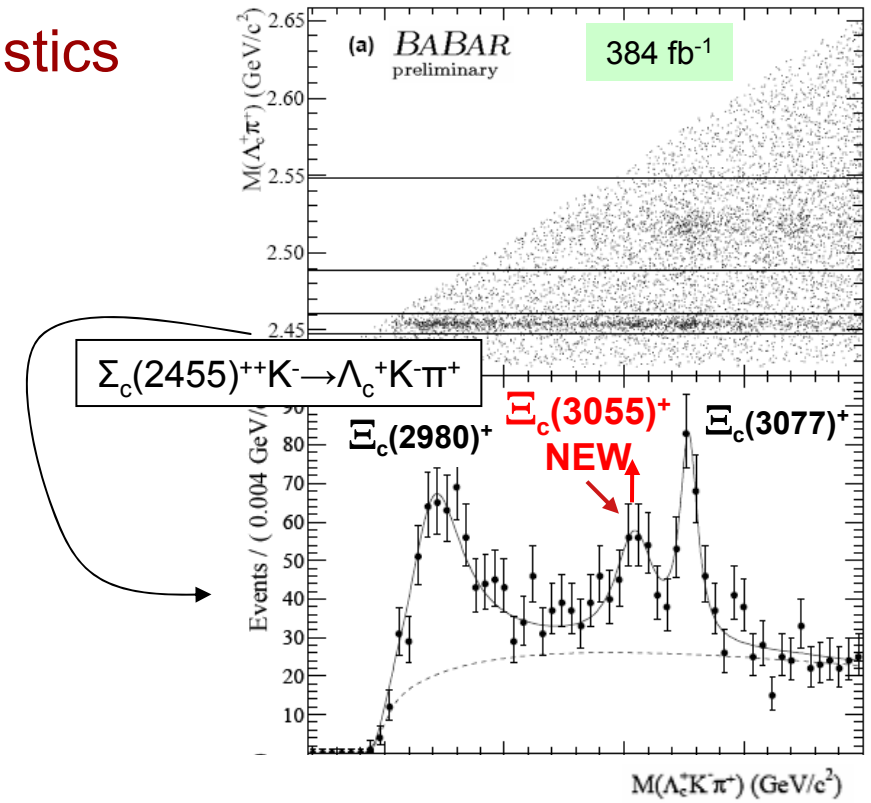


BaBar: Preliminary

DISCOVERY OF $\Xi_c(3055)^+$ AND $\Xi_c(3123)^+$ NEW

- Updated analysis with more statistics
- New state (looking in the $\Sigma_c(2455)^{++}$ band):

$\Xi_c(3055)^+$	
Mass (MeV/c^2)	$3054.2 \pm 1.2 \pm 0.5$
Width (MeV)	$17 \pm 6 \pm 11$
Yield	$218 \pm 53 \pm 79$
Significance	6.4σ



BaBar: Preliminary

DISCOVERY OF $\Xi_c(3055)^+$ AND $\Xi_c(3123)^+$ NEW

- Updated analysis with more statistics
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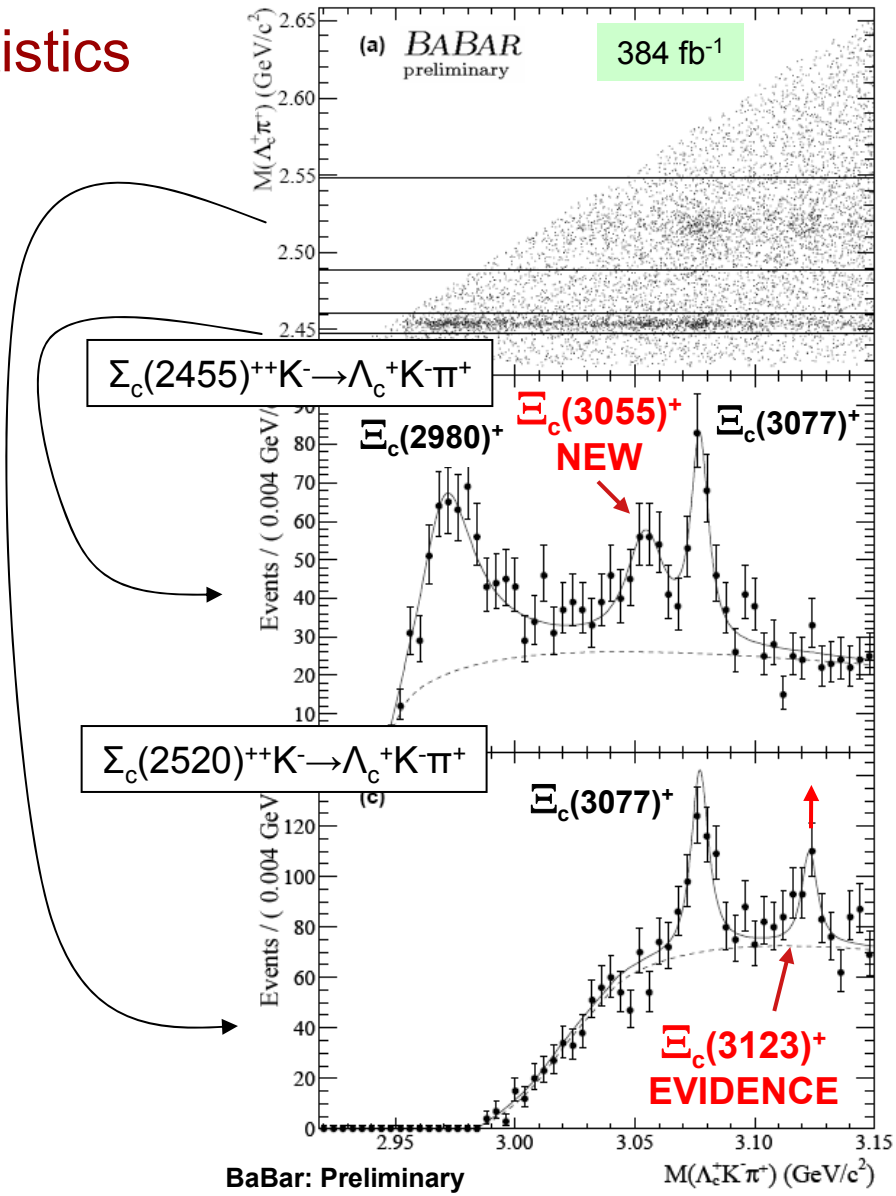
Width (MeV)	$17 \pm 6 \pm 11$
Yield	$218 \pm 53 \pm 79$
Significance	6.4σ

- Evidence for (looking in the $\Sigma_c(2520)^{++}$ band):

$\Xi_c(3123)^+$	
Mass (MeV/c^2)	$3122.9 \pm 1.3 \pm 0.3$
Width (MeV)	$4.4 \pm 3.4 \pm 1.7$
Yield	$101 \pm 34 \pm 9$
Significance	3.6σ



CONCLUSIONS

- Tens of new charmed states have been discovered since 1999, beginning of BaBar!

- $c\bar{s}$ summary:
  - $\mathbf{D_{s0}^{*}(2317)}$, $\mathbf{D_{s1}(2460)}$: well determined experimentally, not understood theoretically
  - $\mathbf{D_{sJ}^{*}(2860)}$, $\mathbf{D_{sJ}(2700)}$: still unclear experimentally and theoretically

- Charmed baryons
  - Many states studied by BaBar: Ω_c^0, $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$
  - Many new states discovered: Ω_c^{*0}, $\Lambda_c(2940)$, $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$

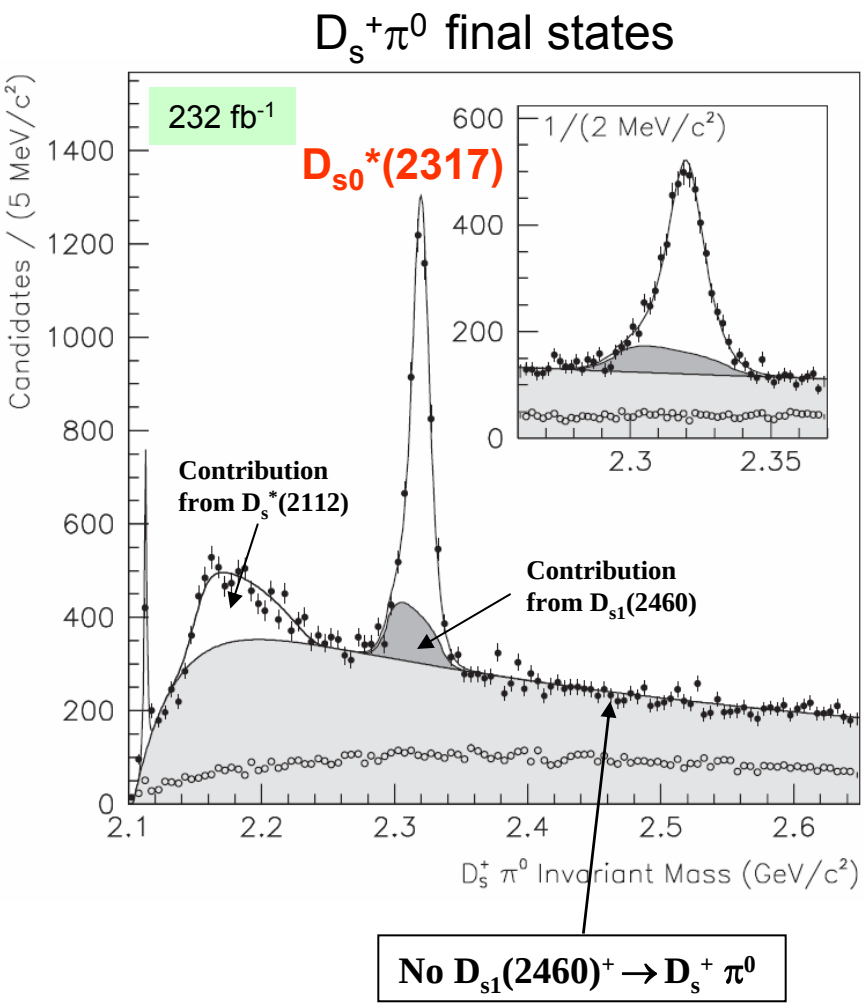
Experimental status:

- Lots of on-going analyses with the current dataset
  - More **decay modes** investigated to understand these resonances
- BaBar is taking data till Sept. 2008
- Lots of new data to analyse!
  - We can bet that more **surprises** will arise!

ADDITIONAL SLIDES

$D_{s0}^*(2317)$ IN INCLUSIVE DATA

- Study of $e^+e^- \to c\bar{c}$ events
  - Resonance in $D_s^+\pi^0$
- Complex kinematics with competing contributions and mutual cross-feed
- Properties
  - $M = (2319.6 \pm 0.2 \pm 1.4)$ MeV/c^2
  - $\Gamma < 3.8$ MeV at 95% CL
- No decay to $D_s^+\pi^+$ or $D_s^+\pi^-$
  - No indication of **isospin partners**
  - **4 quark** model disfavored

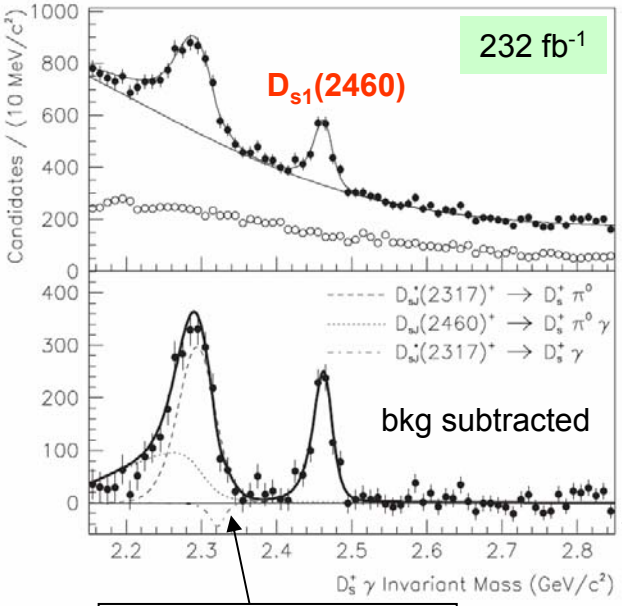


BaBar: Phys. Rev. D74 (2006) 032007

$D_{s1}(2460)$ IN INCLUSIVE DATA

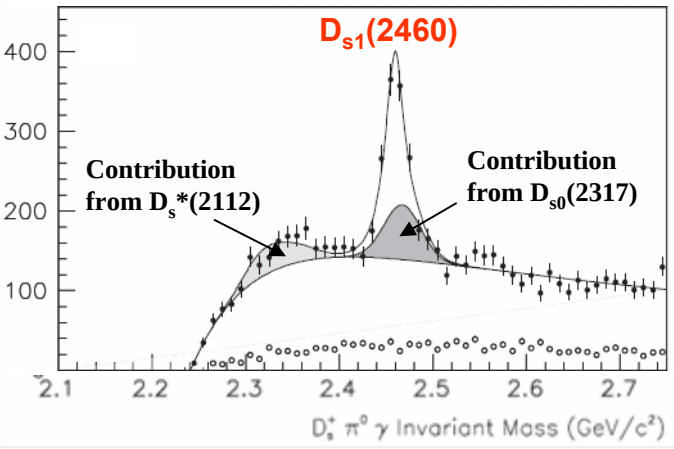
- $D_{s1}(2460)$ observed in 3 decay final states

$D_s^+ \gamma$ final states

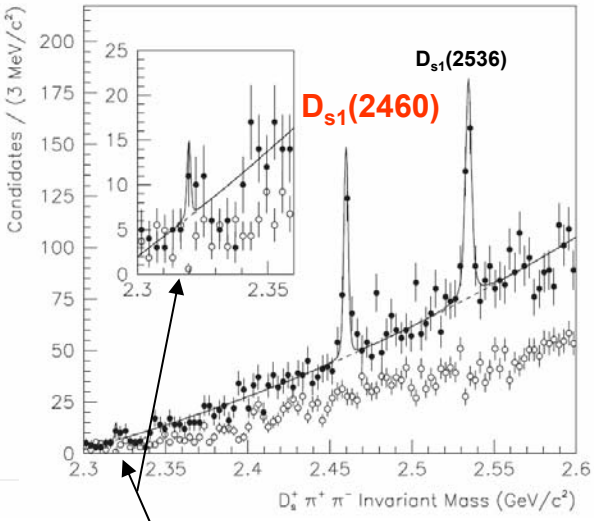


No $D_{s0}^*(2317)^+ \to D_s^+ \gamma$

$D_s^+ \pi^0 \gamma$ final states



$D_s^+ \pi^+ \pi^-$ final states



No $D_{sJ}^*(2317)^+ \to D_s^+ \pi^+ \pi^-$

- Properties
  - M = (2460.1 ± 0.2 ± 0.8) MeV/c^2
  - Γ < 3.5 MeV at 95% CL

No search for $D_s^+ \pi^{+/-} \pi^0$ isospin partners as yet

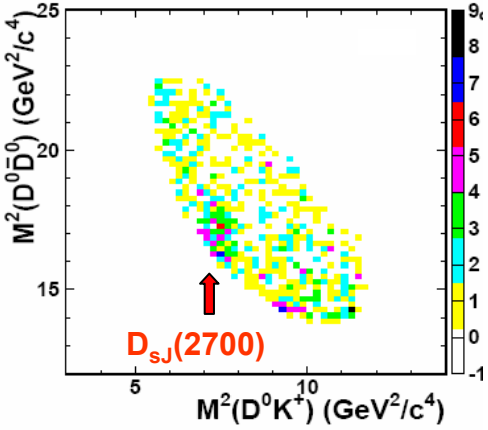
BaBar: Phys. Rev. D74 (2006) 032007

EVEN MORE STATES: $D_{sJ}(2700)$

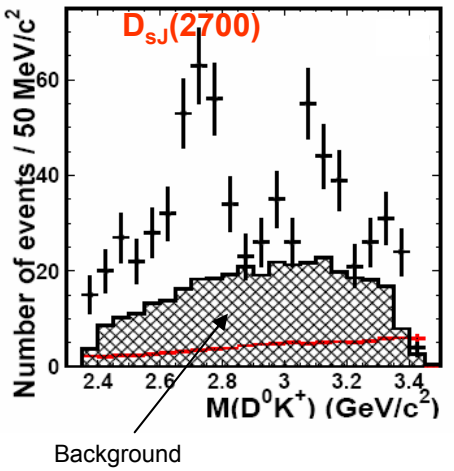
- Study of $B^+ \to \bar{D}^0 D^0 K^+$
  - Looking at the **Dalitz plot** and the **D^0K^+** projection
- New resonance decaying to D^0K^+
  - $B^+ \to \bar{D}^0 D_{sJ}$, $D_{sJ} \to D^0K^+$
  - $M = (2715 \pm 11\ ^{+11}_{-14})$ MeV/c^2
  - $\Gamma = (115 \pm 20\ ^{+36}_{-32})$ MeV
  - $J^P = 1^-$ favored
- Same resonance as seen by BaBar in continuum, X(2690)?
  - Mass and width consistent, same decay mode
- Interpretation?
  - $c\bar{s}$ state $\mathbf{2^3S_1}$?
    - expected mass at 2720 MeV/c^2
  - **Chiral symmetry**: 1^+ - 1^- doublet paired with $D_{s1}(2536)$?

Phys.Polon. B 35, 2377 (2004)

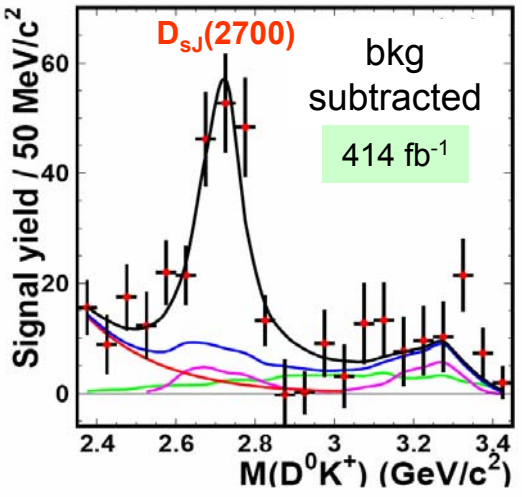
Dalitz plot

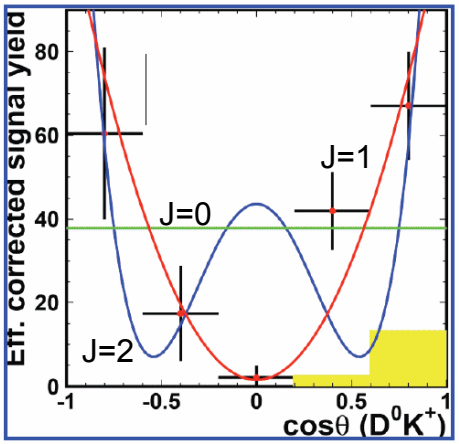


D^0K^+ projection



D^0K^+ projection



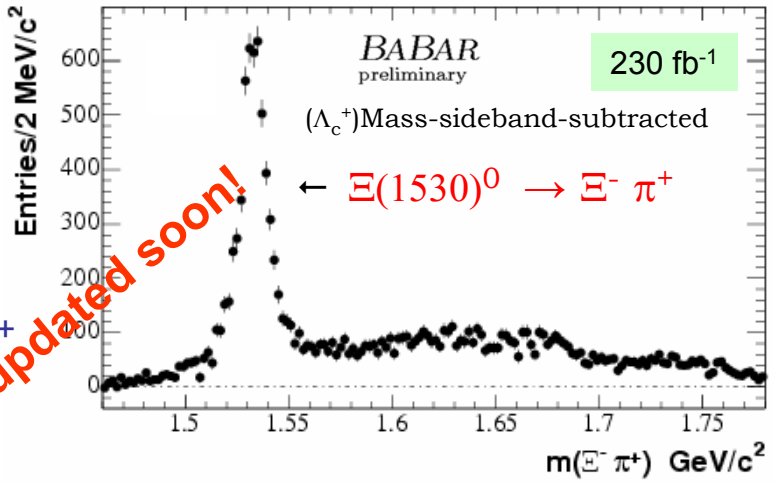


Belle: hep-ex/0707.3491

STUDY OF $\Xi(1530)^0$ AND $\Xi(1690)^0$

$\Xi(1530)^0$ from $\Lambda_c^+ \rightarrow (\Xi^- \pi^+) K^+$

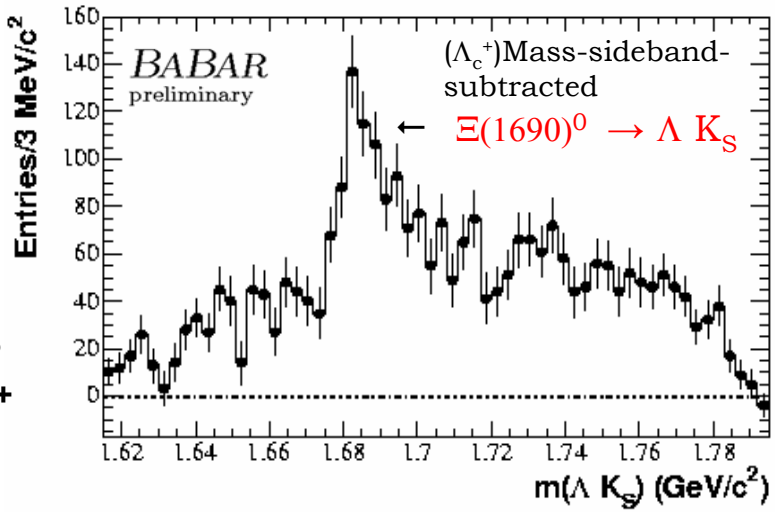
- Use of Legendre polynomial moments to determine the spin
  - Spin **3/2** clearly established
  - Using previous results: P-wave $3/2^+$
- Showed the presence of an S-wave $\Xi^- \pi^+$ amplitude, with some indication of a $\Xi(1690)$ S-wave contribution



Both results to be updated soon!

$\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda \bar{K}^0) K^+$

- Legendre polynomial moments
  - Spin **1/2** preferred
- Fitting now the whole Dalitz Plot
  - to get more precise **(M,Γ)** measurements
  - to show the existence of $\Lambda_c^+ \rightarrow \Lambda\, a^0(980)^+$



BaBar: Thesis SLAC-R-868