Charmed Particles Production in $e^+e^- \rightarrow c\bar{c}$ at 10.6 GeV

Simone Pacetti

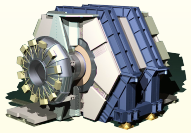
Laboratori Nazionali di Frascati

On behalf of the BABAR Collaboration

Workshop
parton fragmentation processes in the vacuum and in the medium

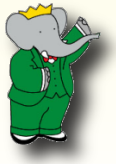
ECT* - Trento, February 25-29, 2008

Outline



BABAR as *c*-factory

- **Charmed Mesons**
  - $D_{s0}^*(2317)$ and $D_{s1}(2460)$
  - **New states** $D_{sj}^*(2860)$ and $X(2690)$
- **Charmed Baryons**
  - Ω_c and **discovery** of Ω_c^*
  - **New state** $\Lambda_c(2940)$
  - **New states** $\Xi_c(3055)$ and $\Xi_c(3123)$
  - Events with both a Λ_c^+ and a $\overline{\Lambda}_c^-$
- **Summary**



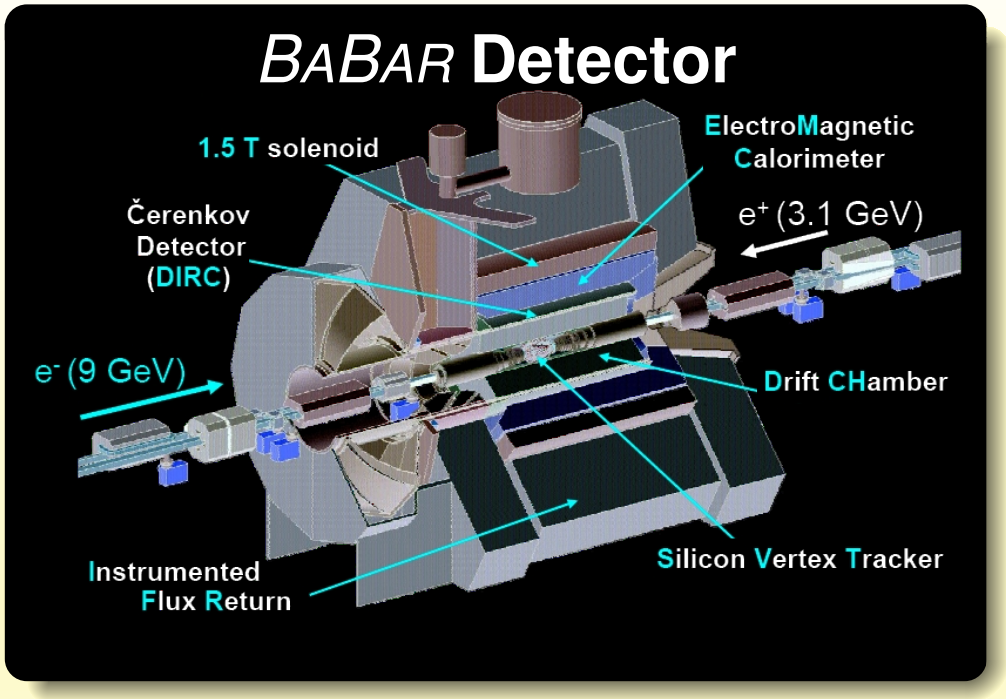
BABAR *b* and *c* factory

e^+e^- Collider: PEP-II at SLAC

CM energy: 10.58 GeV

Peak luminosity: $1.2 \cdot 10^{34} \mathrm{cm}^{-1}\mathrm{s}^{-1}$

$$\int_{\text{October 99}}^{\text{August 07}} \mathcal{L}dt = 447\ \mathrm{fb}^{-1}$$

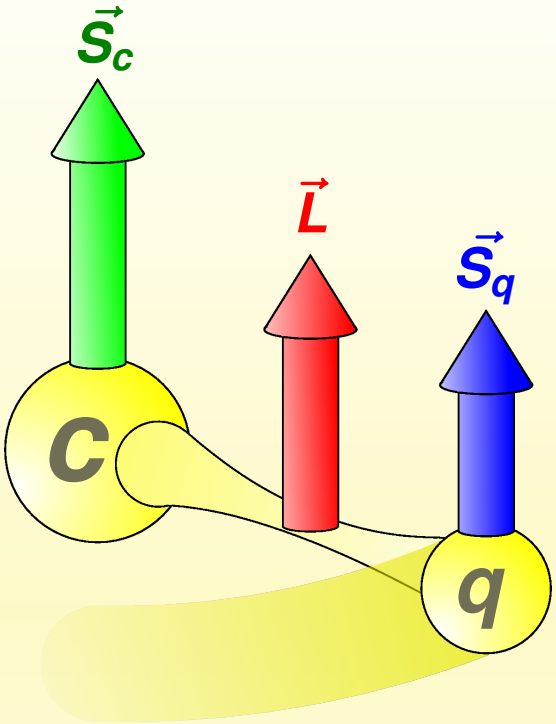


$$\sigma(b\bar{b}) = 1.05\,\mathrm{nb} \quad \sigma(c\bar{c}) = 1.30\,\mathrm{nb} \Rightarrow N(b\bar{b}) = 4.7 \cdot 10^8 \quad N(c\bar{c}) = 5.8 \cdot 10^8$$

$e^+e^- \to c\bar{c}$ produces high-p charmed particles $\Rightarrow$ **clean** signals even for **rare** particles

Charmed meson mass splitting from HQET

hep-ph/9611411

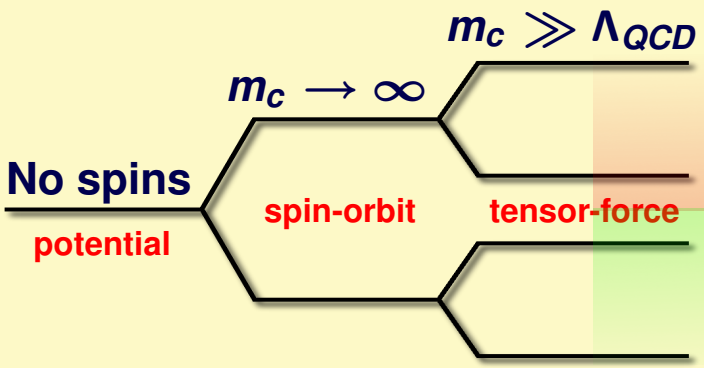


Heavy Quark Effective Theory

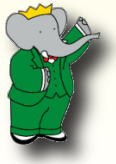
works well for Charm meson spectroscopy

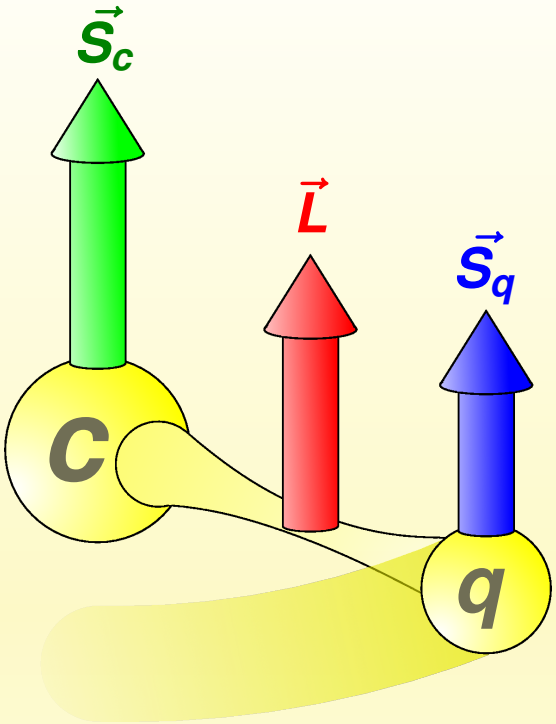
- The spin $\vec{S}_c$ of the heavy quark decouples
- $\vec{j}_q = \vec{L} + \vec{S}_q$ is a good quantum number
- States are described by (S_{c3}, j_q)

$L = 1$ states



j_q	J^P	Decays	Dominant	Γ(MeV)
3/2	2^+	$D^{(*)}\pi$	D-wave: $\frac{3}{2}^+ \to \frac{1}{2}^- 0^-$	~ 20
	1^+	$D^{(*)}\pi$		
1/2	1^+	$D^*\pi$	S-wave: $\frac{1}{2}^+ \to \frac{1}{2}^- 0^-$	> 100
	0^+	$D\pi$		





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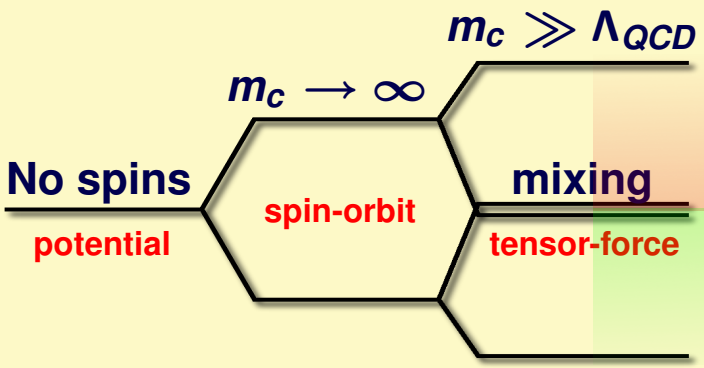

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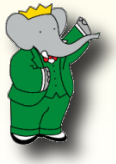
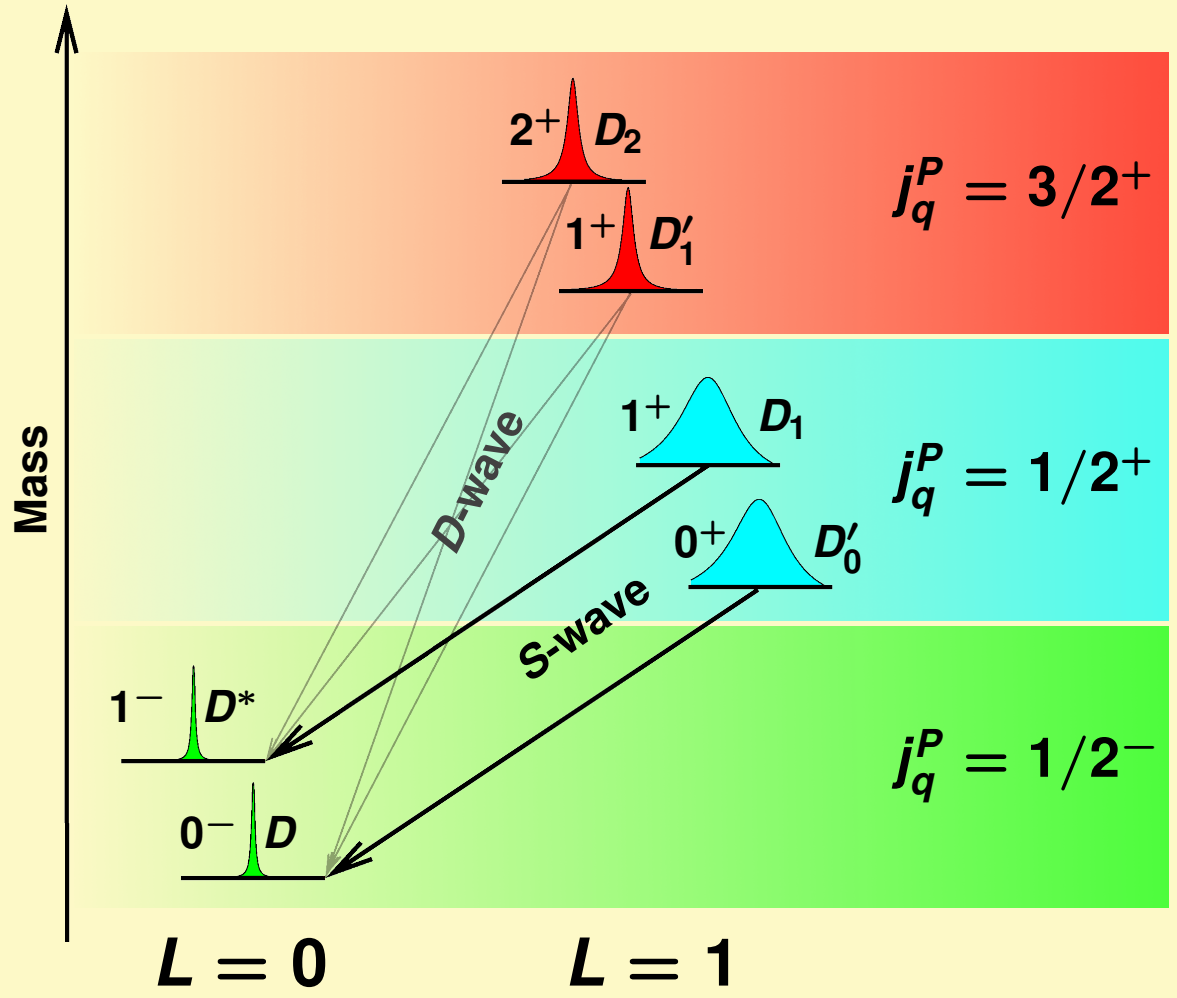
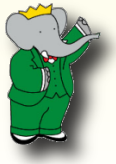


Excited charmed mesons



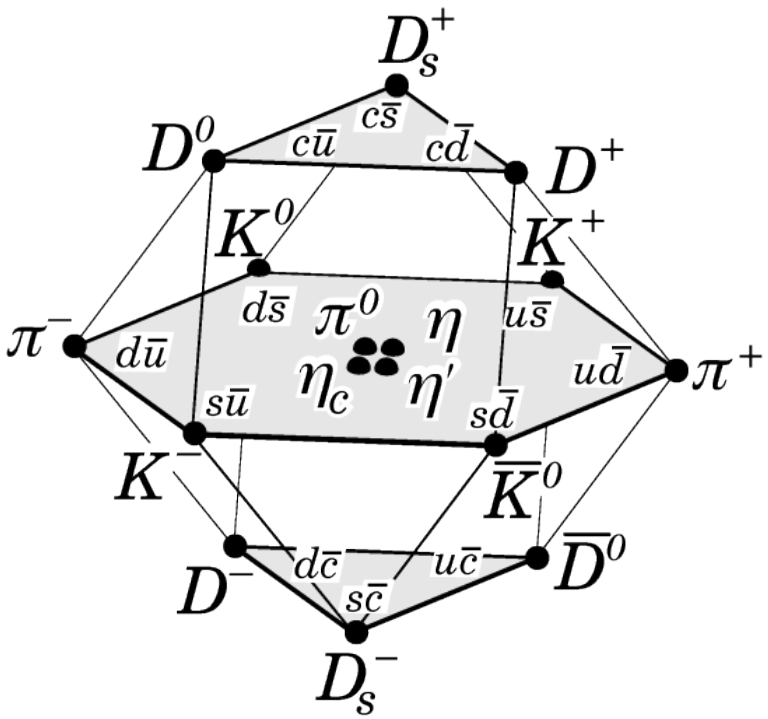
$\Gamma_{D\pi} \sim 20$ MeV

$\Gamma_{D\pi} \sim 100$ MeV

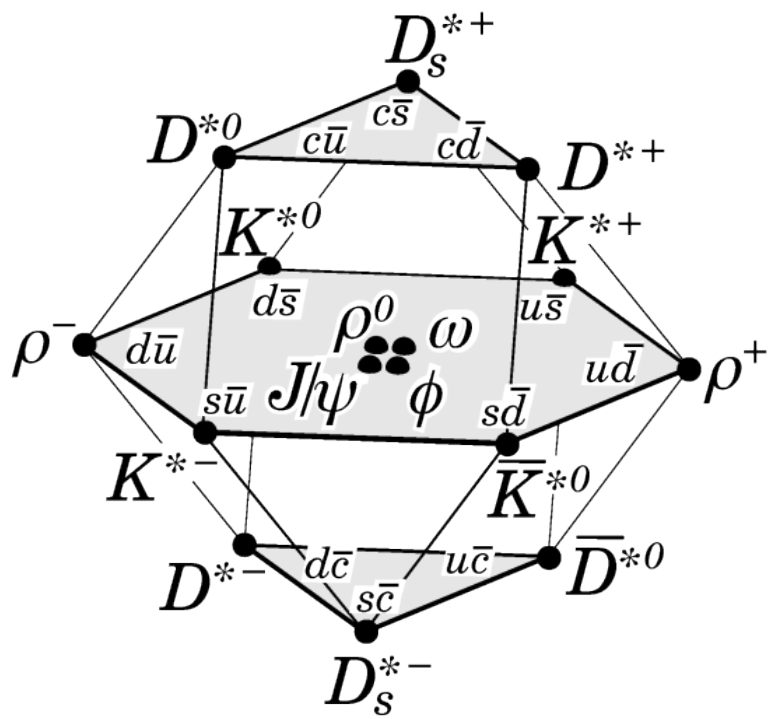


Charmed-strange mesons

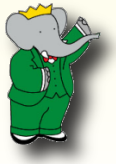
$J^P = 0^-$



$J^P = 1^-$



SU(4) 16-plets with $L = 0$



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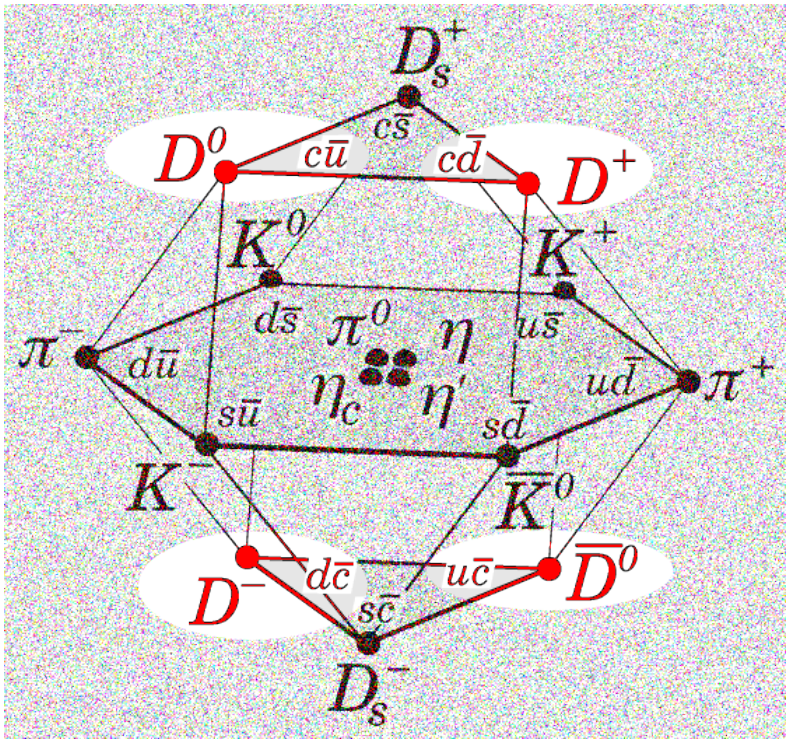

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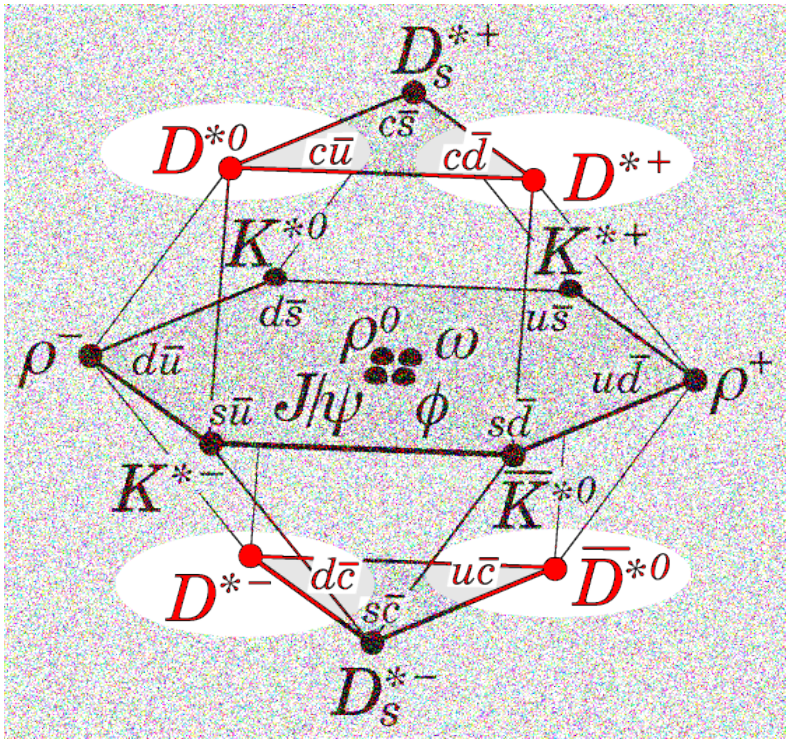
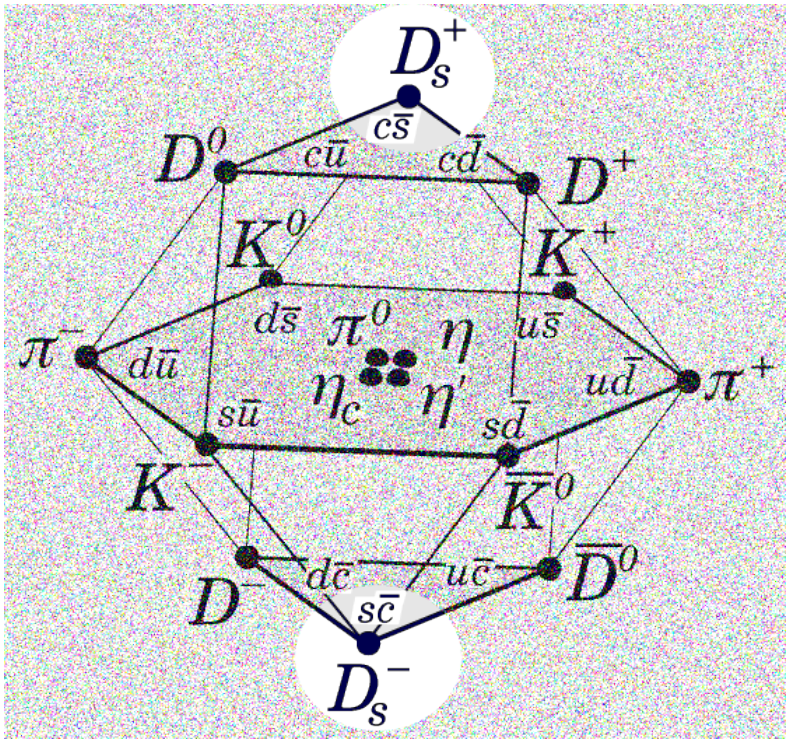


Charmed-light mesons

$$D = c\bar{q}$$
$$(q = u,\ d)$$

Charmed-strange mesons

$J^P = 0^-$



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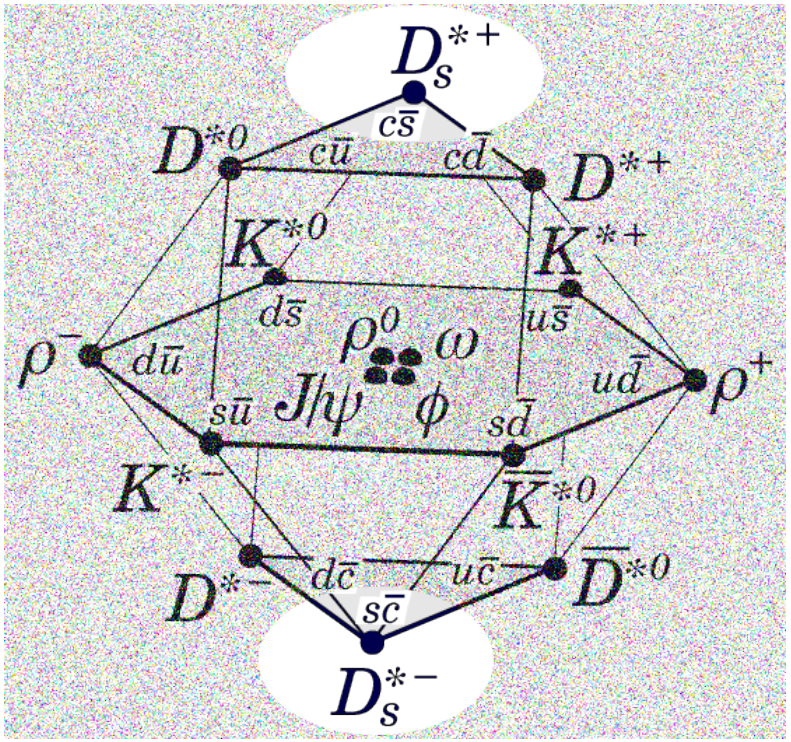
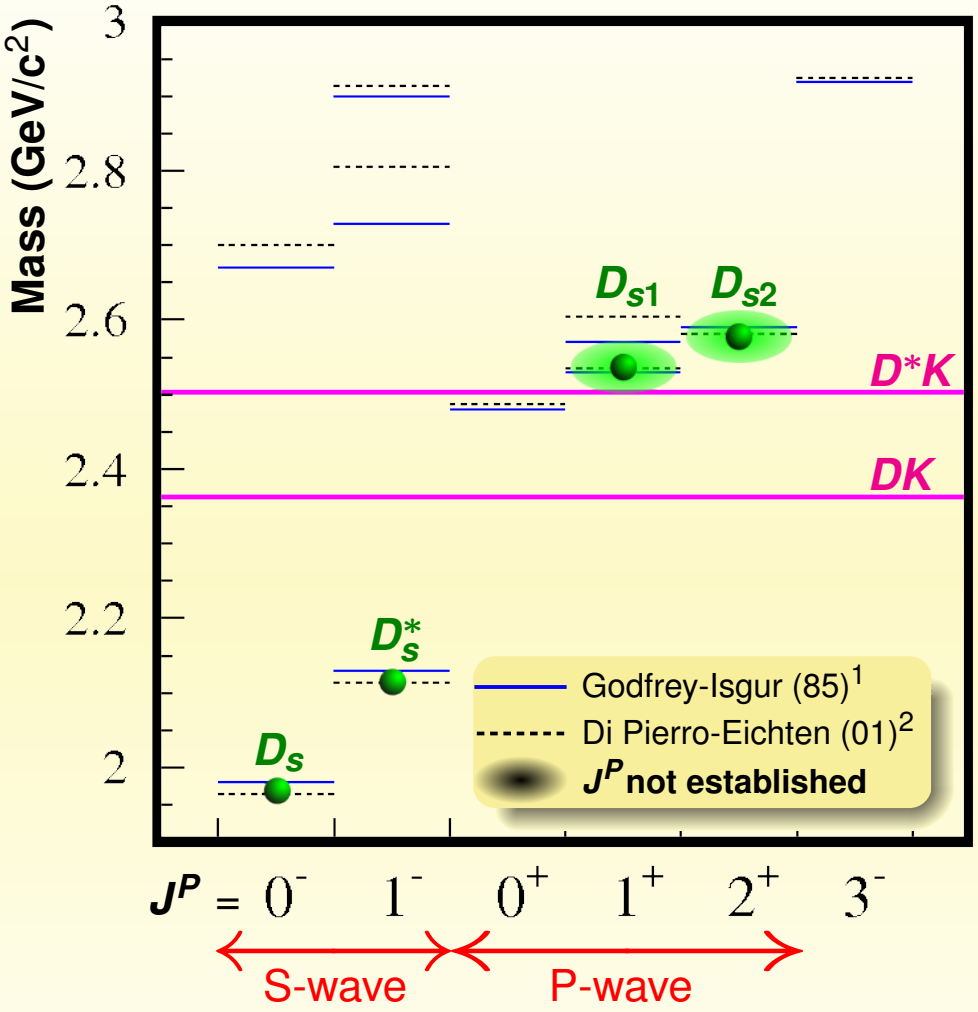


Charmed-strange mesons

$$D_s = c\bar{s}$$

Charmed-strange mesons: the situation



[1] PRD32 189
[2] PRD64 114004

- **Prior to *B*-factories, 4 states:**

  $D_s(1968)$, $D_s^*(2112)$, $D_{s1}(2536)$, $D_{s2}(2573)$

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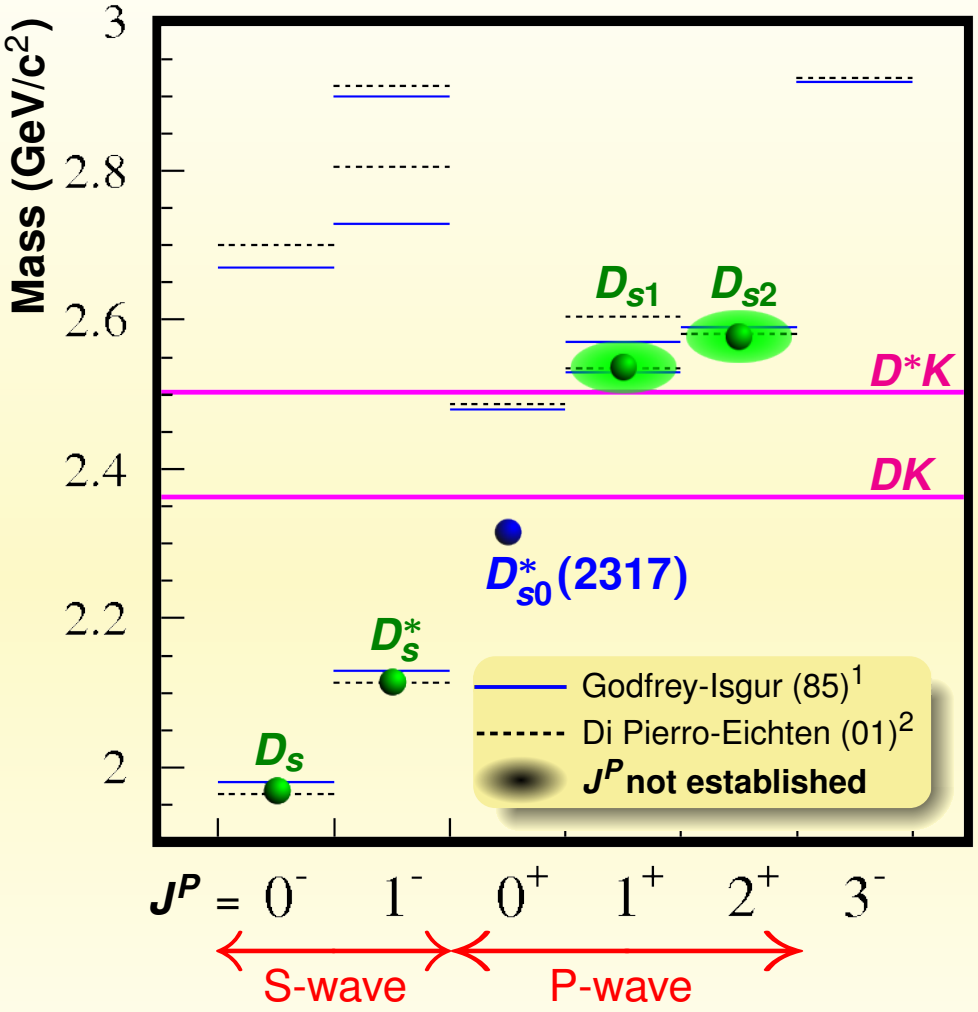

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  narrow $D^*_{s0}(2317)^+$

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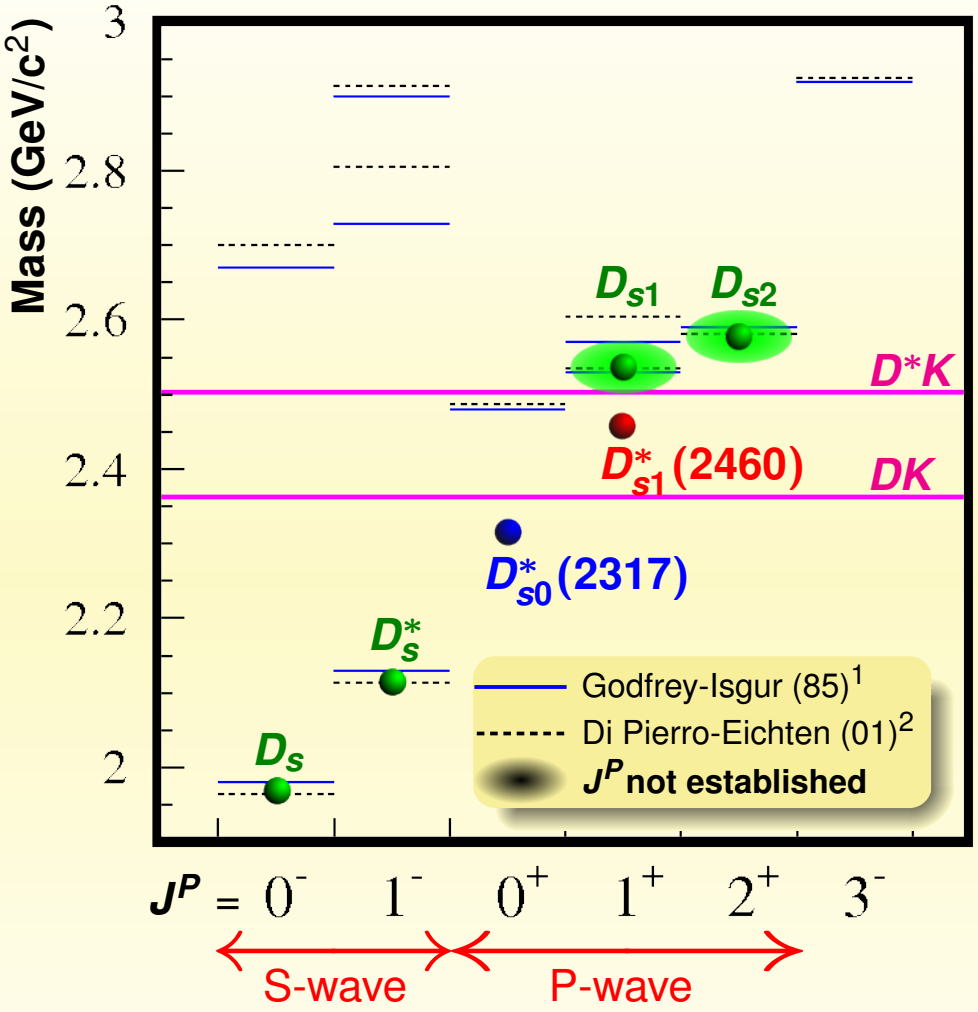

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- **May 2003, CLEO and *BABAR* :**
  narrow $D_{s1}(2460)^+$

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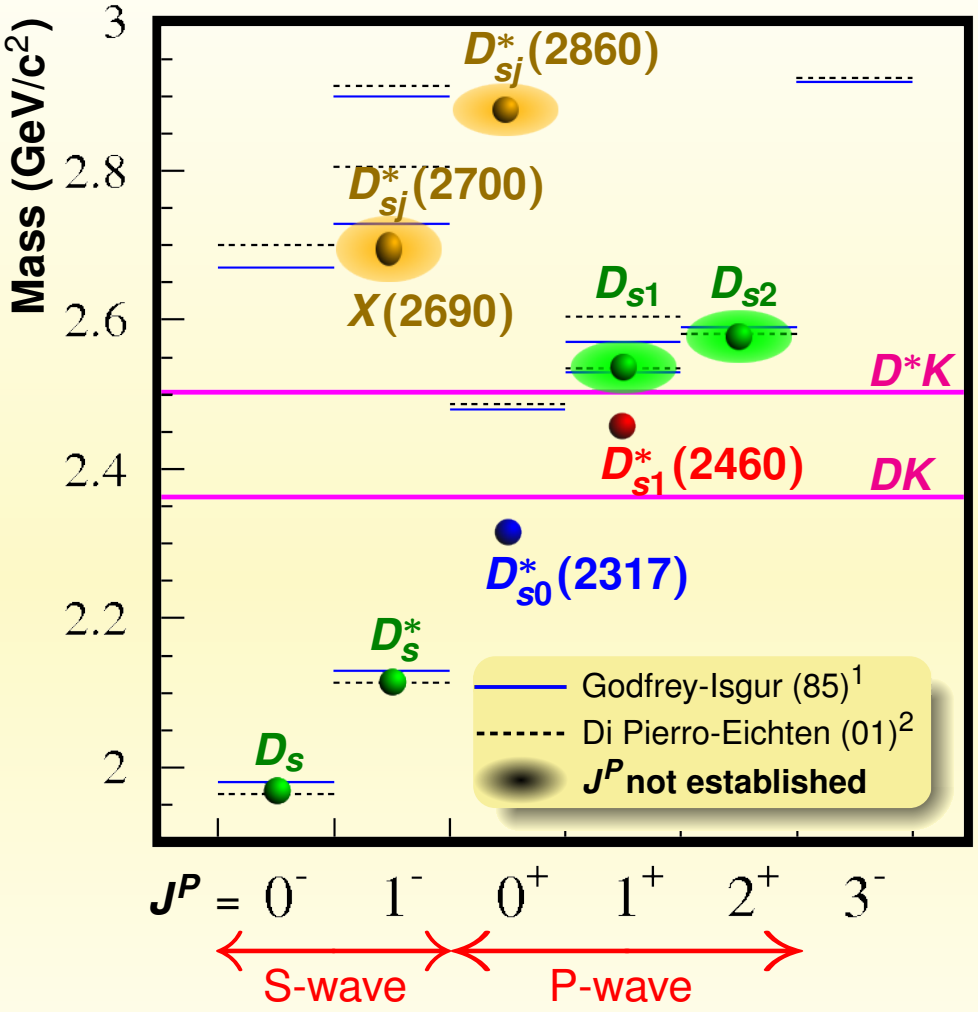

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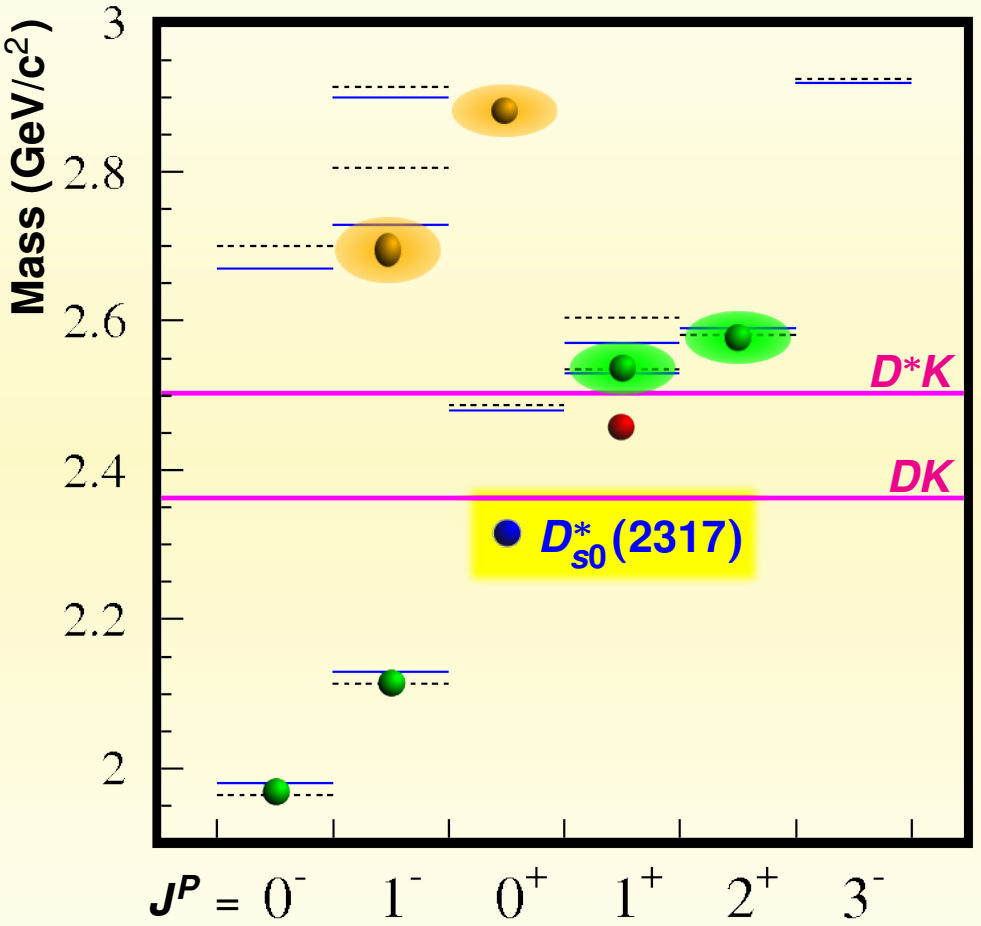
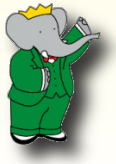
- April 2003, *BABAR* :
  narrow $D_{s0}^*(2317)^+$
- May 2003, CLEO and *BABAR* :
  narrow $D_{s1}(2460)^+$
- July 2006, *BABAR* :
  $D_{sj}^*(2860)^+$ and broad $X(2690)^+$
- July 2006, Belle:
  $D_{sj}^*(2700)^+$ [$\equiv X(2690)^+$?]



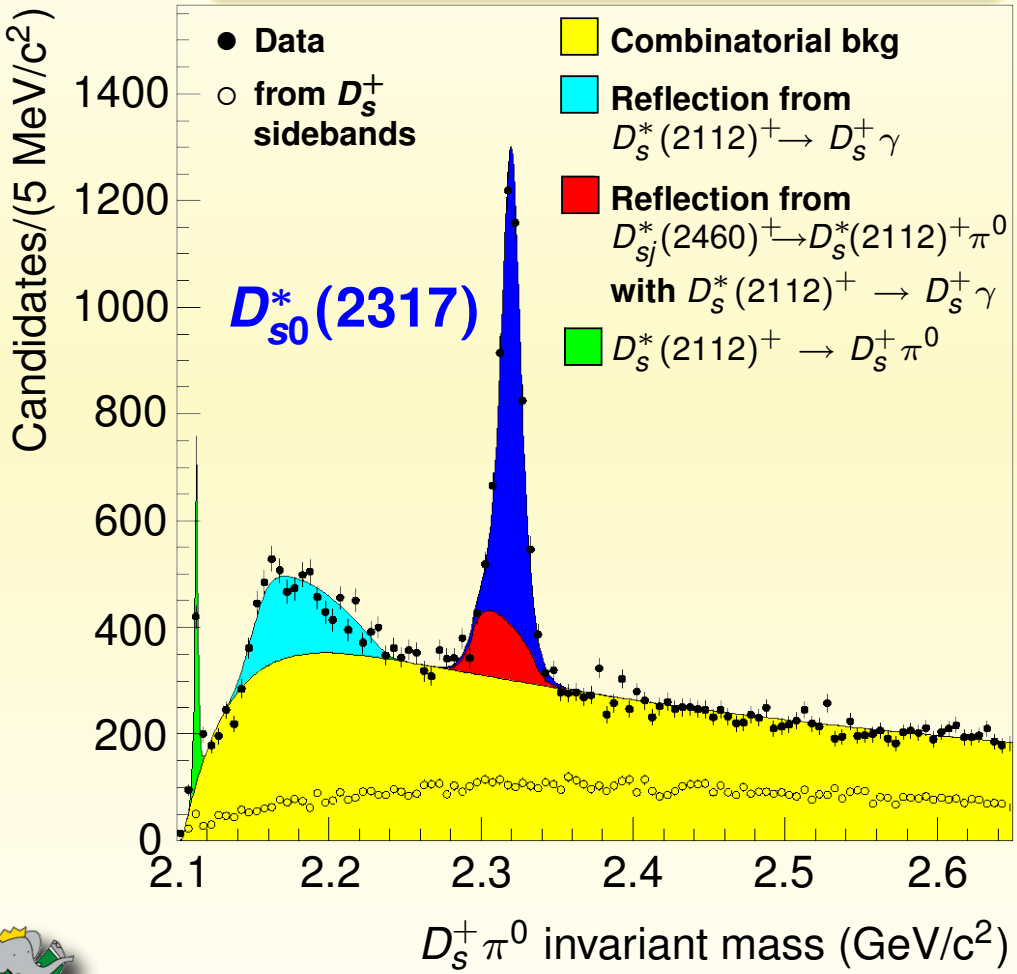
Conventional $c\bar{s}$ . . .

- $j_s = 1/2$
- $I = 0$
- $J^P = 0^+$
- Mass $<$ *DK* threshold
- *S*-wave decay mode in *DK* is forbidden
- Only radiative and isospin violating decays modes $\Rightarrow$ very narrow



$D^*_{s0}(2317)$

BABAR : PRL90 242001 (03), PRL93 181801 (04)
CLEO: PRD68 032002 (03)
Belle: PRL92 012002 (04), PRL91 262002 (03)



Inclusive production:

$e^+e^- \to \gamma^* \to c\bar{c} \to D_s^+\pi^0 X$

232 fb^{-1} of data at $E_{c.m.} = M_{\Upsilon(4s)}$

Properties:

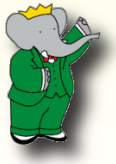
$M = (2319.6 \pm 0.2 \pm 1.4)$ MeV/c^2

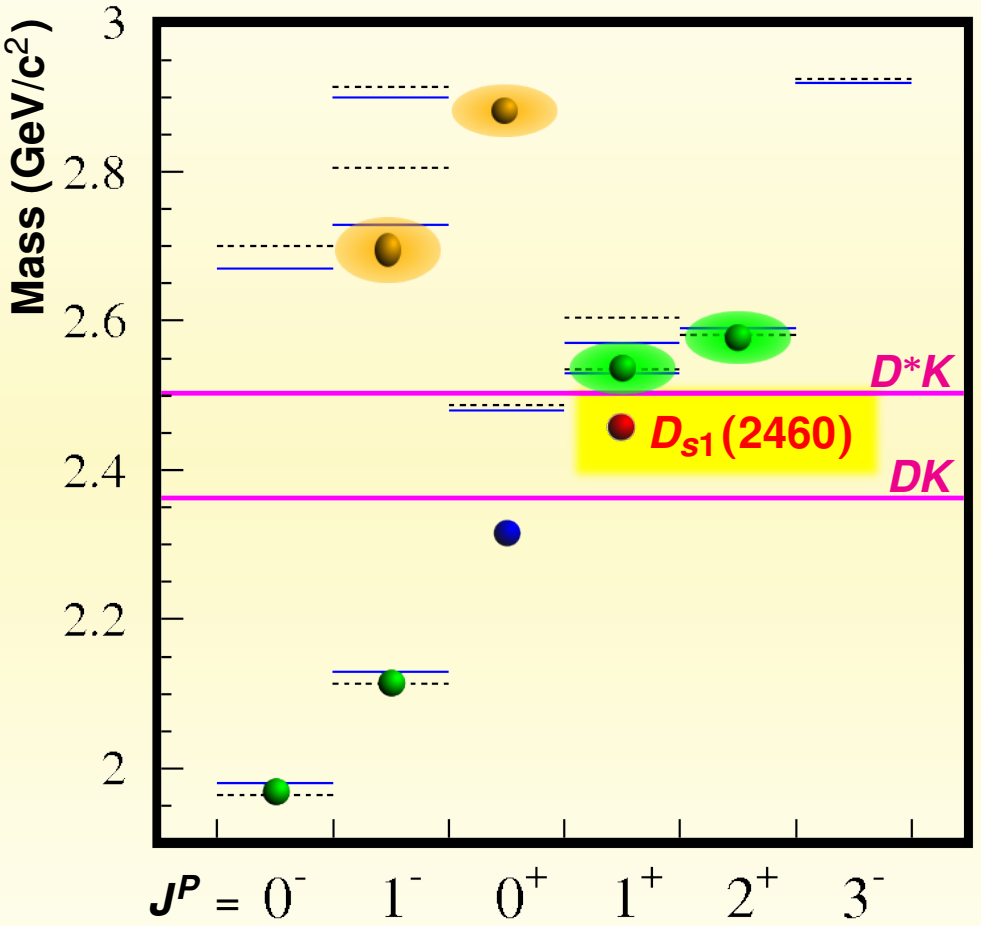
$\Gamma < 3.8$ MeV at 95% C.L.

No indication of isospin partners

No signal for $D_{s1}(2460)^+ \to D_s^+\pi^0$

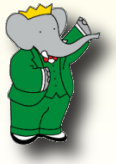
$\sim$ 160 MeV/c^2 below the expectation





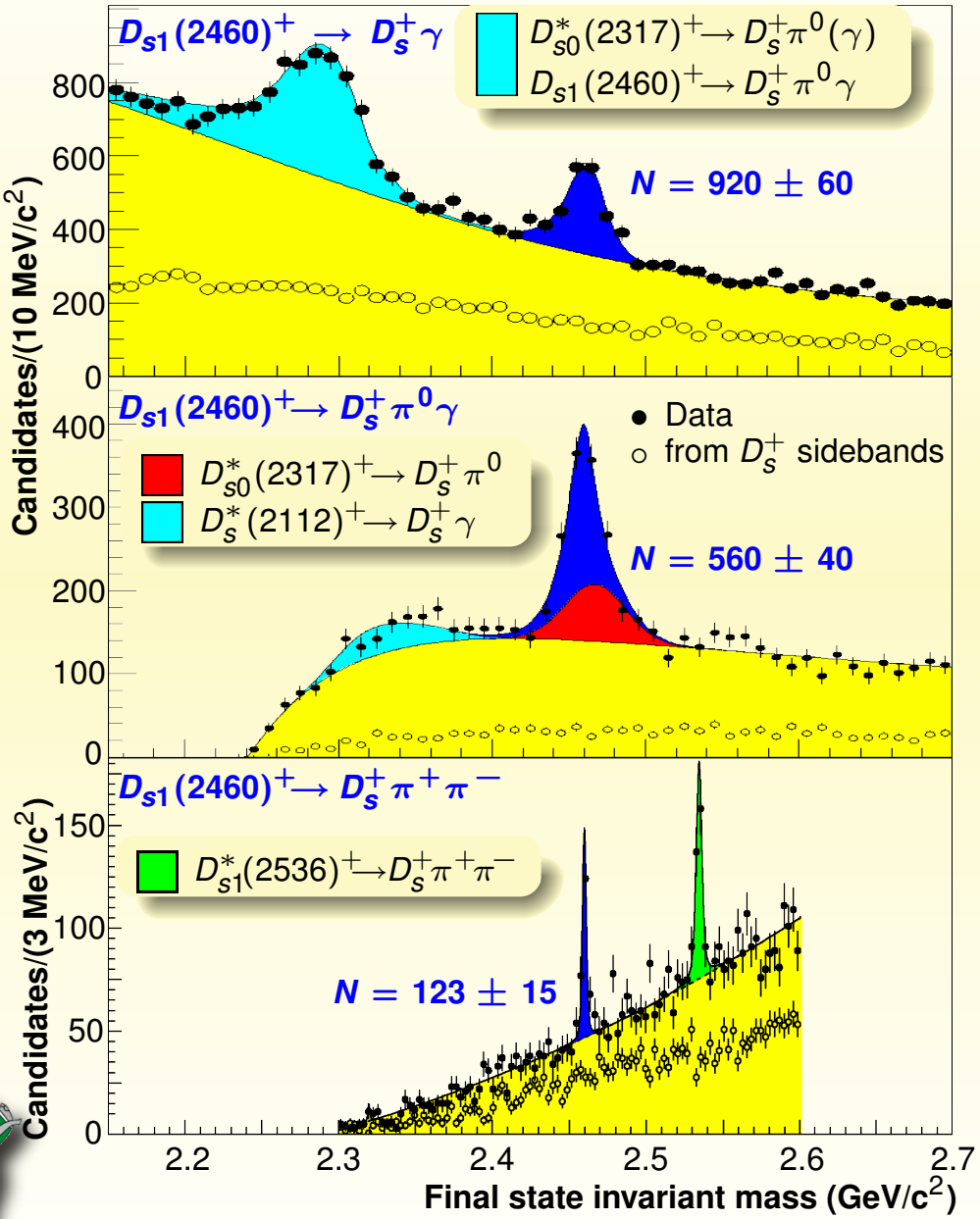
Conventional $c\bar{s}$ . . .

- $j_s = 1/2$
- $I = 0$
- $J^P = 1^+$
- Mass $<$ D^*K threshold
- . . .
- . . .



$D_{s1}(2460)$

PRD74, 032007



BABAR : PRL93 181801 (04)
CLEO: PRD68 032002 (03)
Belle: PRL92 012002 (04), PRL91 262002 (03)

Properties:

$M = (2460.1 \pm 0.2 \pm 0.8)$ MeV/c^2

$\Gamma < 3.5$ MeV at 95% C.L.

Branching fractions:

$$\frac{BR(D_s^+\gamma)}{BR(D_s^+\pi^0\gamma)} = 0.337 \pm 0.036 \pm 0.038$$

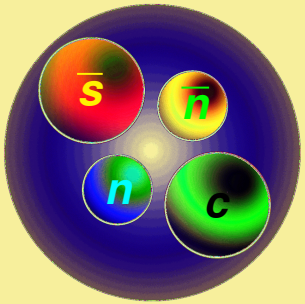
$$\frac{BR(D_s^+\pi^+\pi^-)}{BR(D_s^+\pi^0\gamma)} = 0.077 \pm 0.013 \pm 0.008$$

No indication of isospin partners

Exotic states

see e.g. PRD68, 054006

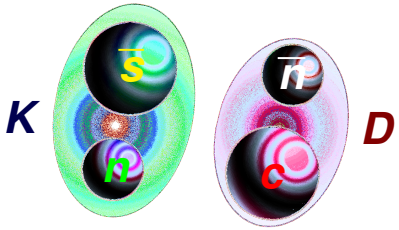
Baryonia



- Single **multiquark cluster**
- Light-quark baryonia are expected to be **extremely broad**
- $I = 1$ $cn\bar{s}\bar{n}$ states are very unstable and decay into $D_s^+\pi$
- $I = 0$ $cn\bar{s}\bar{n}$ states are stable due to isospin conservation ($\not\to D_s^+\pi$) and lie below the DK threshold ($\not\to DK$)

- $I = 1$ partners $cs\bar{n}\bar{n}$ are expected (these states strongly support the baryonium hypothesis)

Molecules



- Pairs of color singlet $q\bar{q}$ weakly bound (e.g. nuclei, hypernuclei and **probably $K\bar{K}$ in light scalars**)
- Same J^{PC} of an $L = 0$ hadron pair
- binding energy ϵ=50-100 MeV
- **Mass 50-100 MeV below the mass of constituents**
- **Strong coupling to the constituent channels**
- Unusual e.m. coupling with respect to the quark model states
- Isospin mixing with large $I = 0$ component

Pieces of evidence of molecular states

see e.g. PRpt454 1

- **Mass comparison between $D_s(c\bar{s})$ and $D(c\bar{n})$ states**

$$L=0 \qquad \left.\begin{matrix} M_{D_s}-M_D \\ M_{D_s^*}-M_{D^*} \end{matrix}\right\} \simeq \left.\begin{matrix} M_{D'_{s1}}-M_{D'_1} \\ M_{D^*_{s2}}-M_{D^*_2} \end{matrix}\right\} \simeq 100\ \mathrm{MeV}/c^2 \qquad L=1,\ j_q=\tfrac{3}{2}$$

$$L=1,\ j_q=\tfrac{1}{2}$$
$$M_{D^*_{s0}}-M_{D^*_0}=-86\ \mathrm{MeV}/c^2$$
$$M_{D_{s1}}-M_{D_1}=37\ \mathrm{MeV}/c^2$$

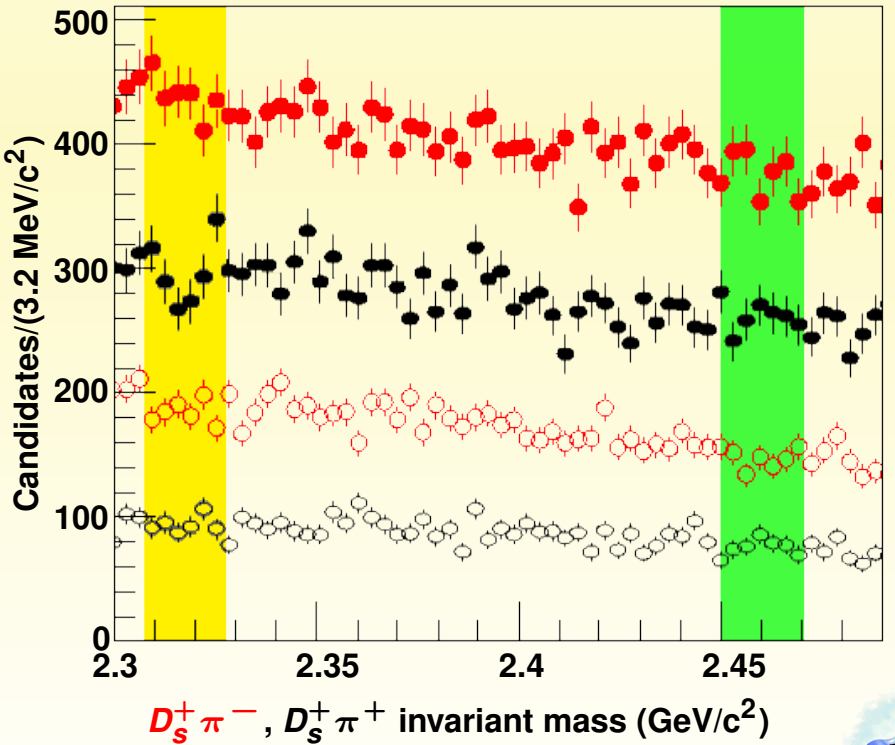
- **Mass comparison between D_s and constituents**

$$\left.\begin{matrix} M_D+M_K-M_{D_{s0}} \\ M_{D^*}+M_K-M_{D^*_{s1}} \end{matrix}\right\} \simeq 50\ \mathrm{MeV}/c^2$$

- **Quantum numbers**

$$D^{*+}_{s0} \to D^+_s\pi^0 \Rightarrow DK\text{: } L=0\ J^P=0^+$$
$$D^+_{s1} \to D^{*+}_s\pi^0 \Rightarrow D^*K\text{: } L=0\ J^P=1^+$$

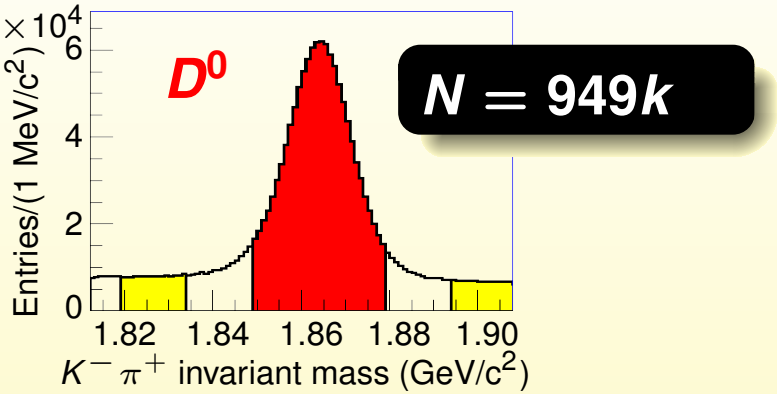
- **No evidence of isospin partners required by the baryonium hypothesis**
- **Isospin mixing allows for $D_s^+\pi^0$ decays**



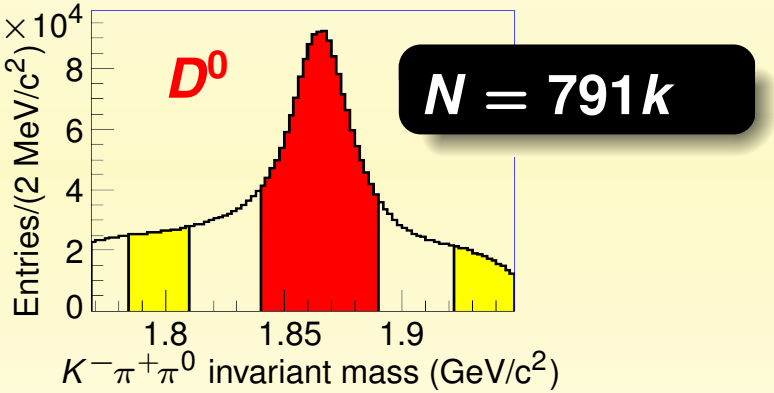
$c\bar{s}$: hep-ph/0703225, PRD72 074004,...

DK system in inclusive data (240 fb^{-1})

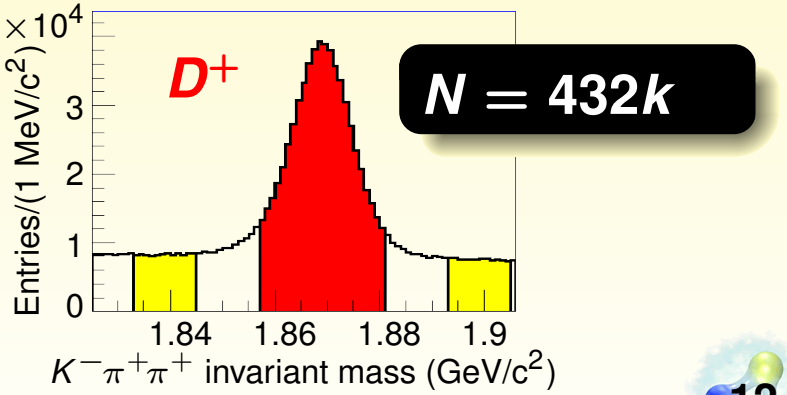
- $e^+e^- \to D^0K^+X$, $D^0 \to K^-\pi^+$

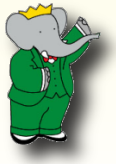


- $e^+e^- \to D^0K^+X$, $D^0 \to K^-\pi^+\pi^0$



- $e^+e^- \to D^+K_SX$, $D^+ \to K^-\pi^+\pi^+$





$D^*_{sJ}(2860)^+$ and $X(2690)^+$

No signal from $D^{0(+)}$ sidebands

Non-resonant background

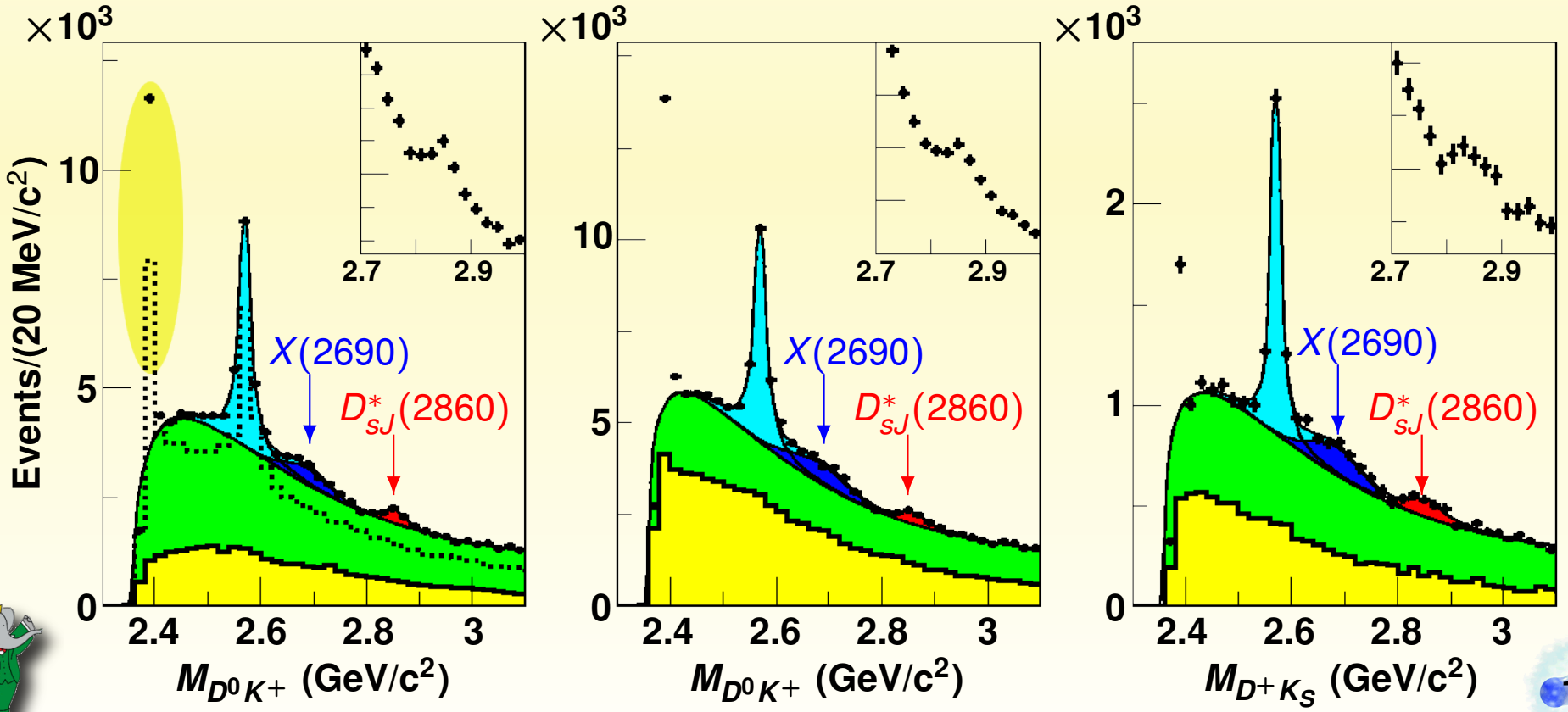
No signal from MC

Reflection: $D_{s1}(2536) \to KD^* \to KD\pi^0(\gamma)$

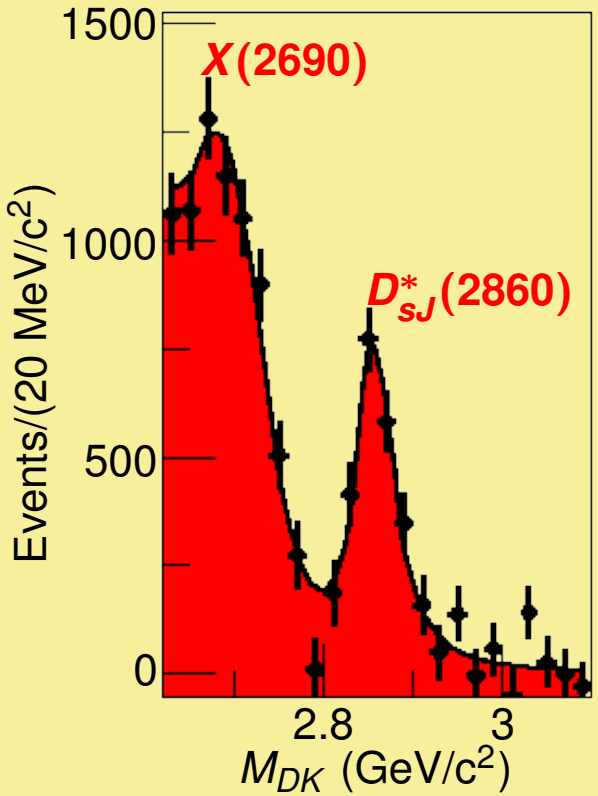
$D_{s2}(2537)^+$

Broad $X(2690)^+$

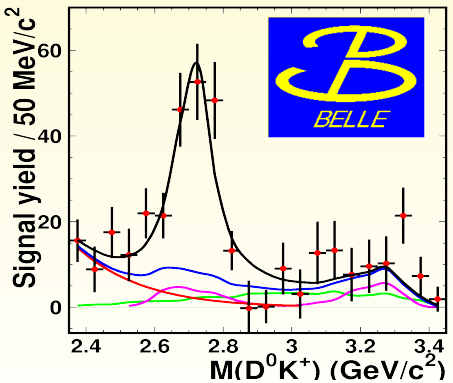
$D_{sJ}(2860)^+$



Total sample (3 modes) background subtracted

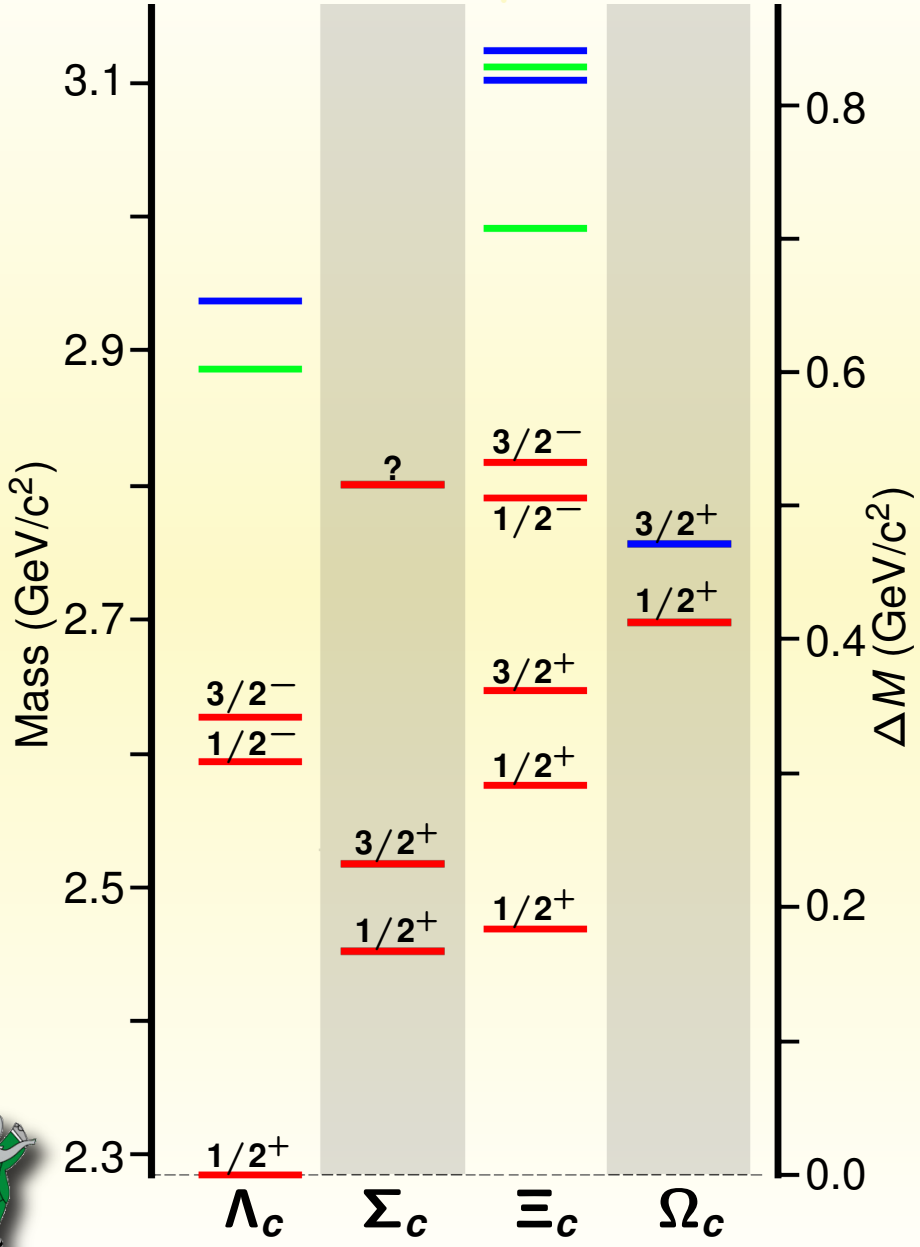


- $D_{sJ}^*(2860)$: Parameters
  - $M = (2856.6 \pm 1.5 \pm 5.0)$ MeV/c²
  - $\Gamma = (47 \pm 7 \pm 10)$ MeV
  - $J^P = 0^+, 1^-, 2^+, \ldots$
- $D_{sJ}^*(2860)$: Possible interpretation
  - $D_{s0}^*(2317)$ radial excitation [PRL97 202001]
  - $c\bar{s}$ with $J^P = 3^-$ [PLB642 48]
  - $c\bar{s}$ with $J^P = 0^+$ [PLB647 159]
- $X(2690)$: Parameters
  - $M = (2688 \pm 4 \pm 3)$ MeV/c²
  - $\Gamma = (112 \pm 7 \pm 36)$ MeV
  - $M = (2714 \pm 11 \pm 13)$ MeV/c²
    $\Gamma = (115 \pm 20 \pm 34)$ MeV



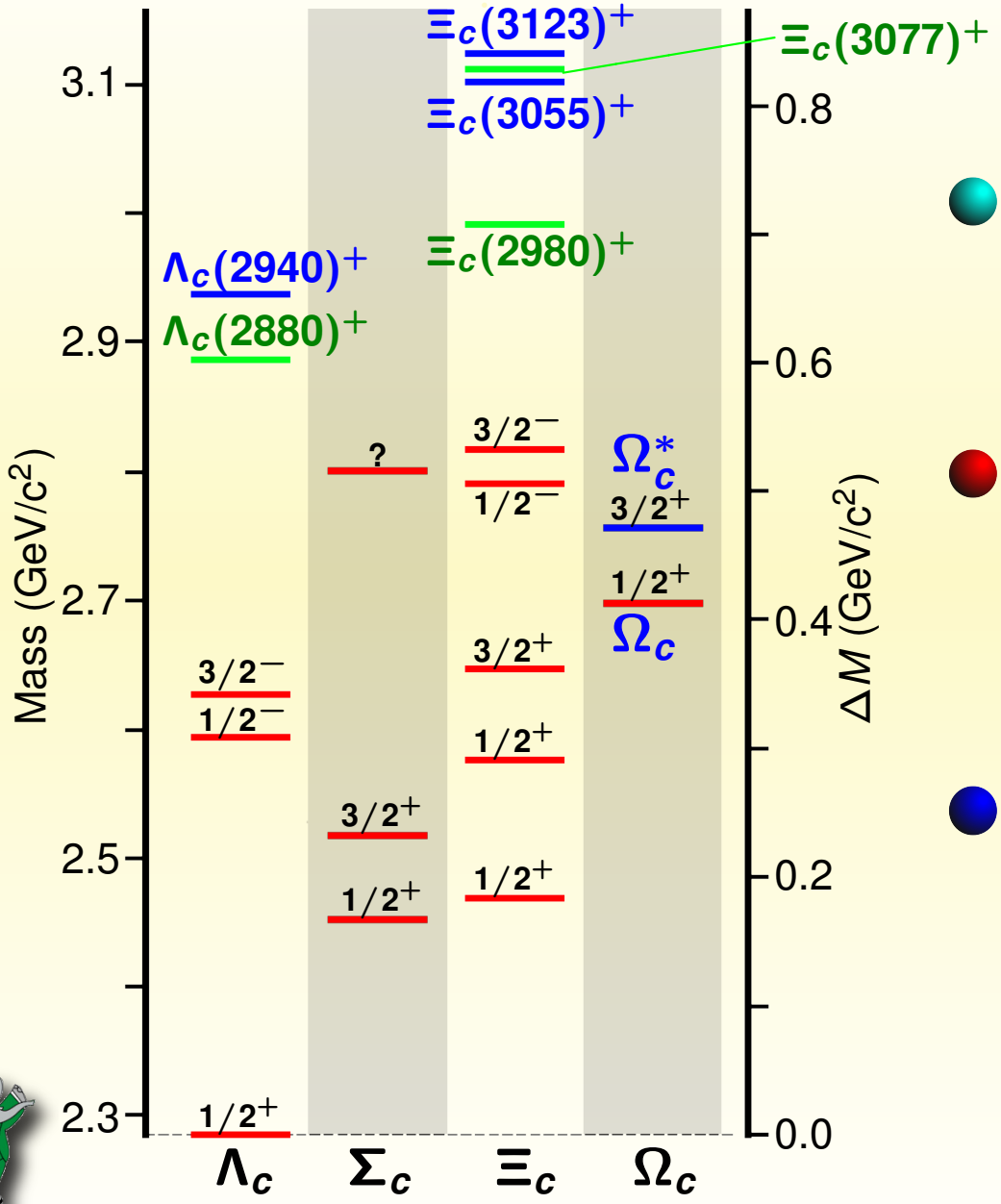
hep-ex/0608031
$B^+ \to \overline{D^0}(D^0 K^+)$

Charmed baryons



- **PDG06: There are twelve known charmed baryons (——)**
- **None of the J^P values has been measured [except perhaps for the lightest $\Lambda_c(1/2^+)$]**

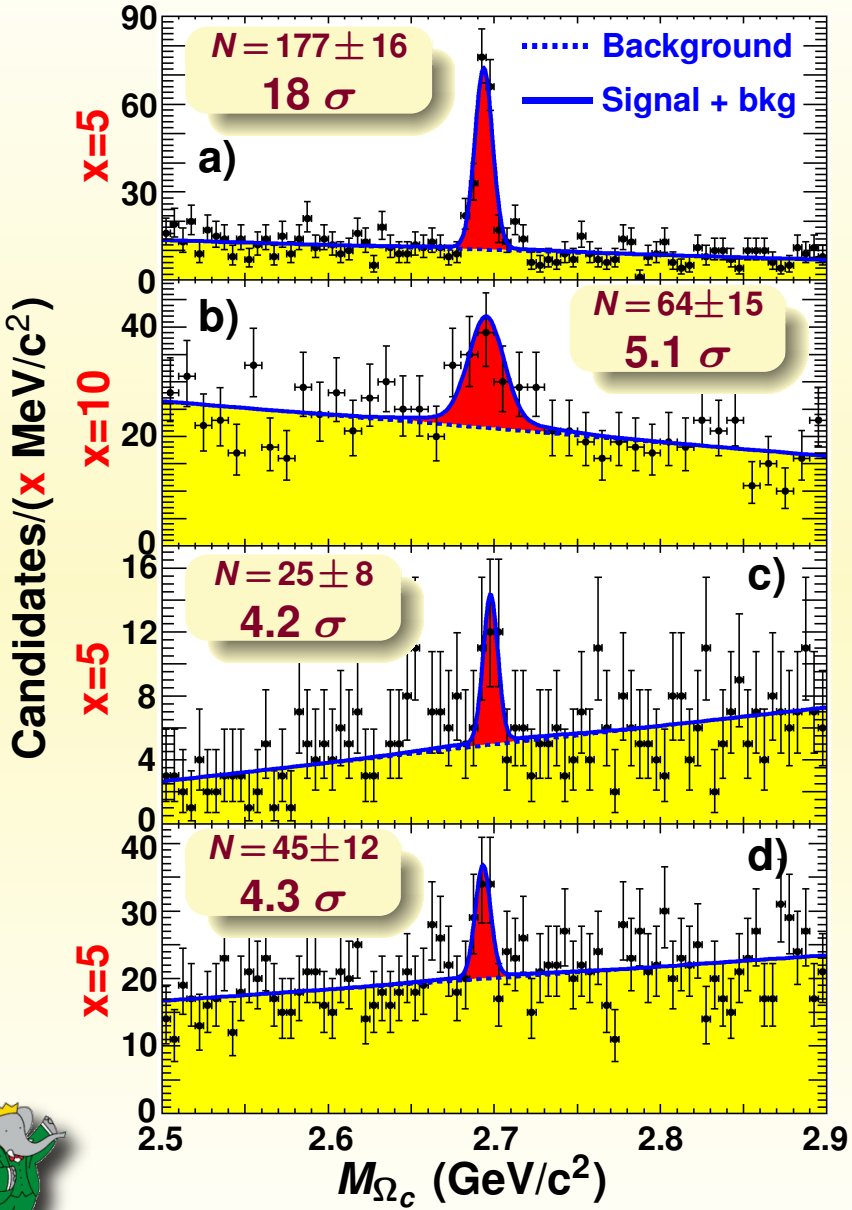
Charmed baryons



- PDG06: There are twelve known charmed baryons (——)
- None of the J^P values has been measured [except perhaps for the lightest $\Lambda_c(1/2^+)$]
- *BABAR* found four new states (——) and Belle found three (——), which we confirmed

Confirmation of Ω_c

PRL99, 062001



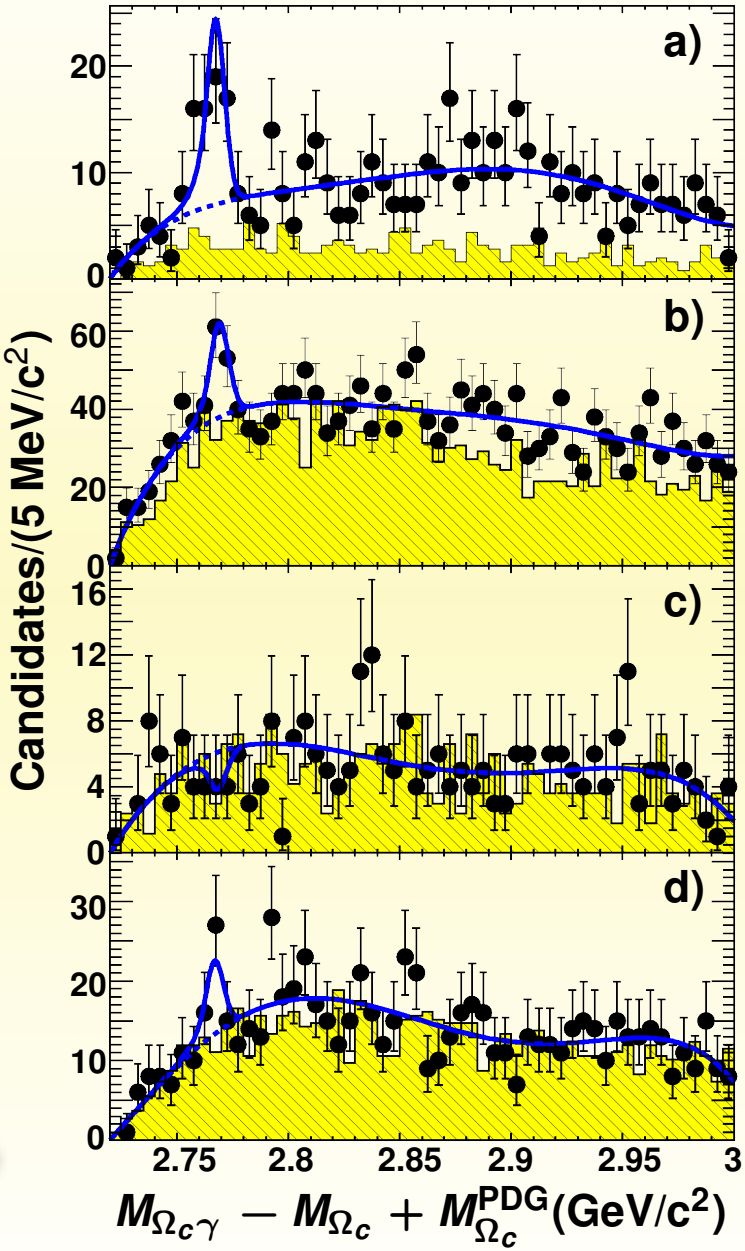
Inclusive data on $e^+e^- \to \Omega_c X$

- $L = 230.7\ \text{fb}^{-1}$
- *css* baryon ground state with $J^P = 1/2^+$
- Samples:
  - a) $\Omega_c \to \Omega^- \pi^+$
  - b) $\Omega_c \to \Omega^- \pi^+ \pi^0$
  - c) $\Omega_c \to \Omega^- \pi^+ \pi^+ \pi^-$
  - d) $\Omega_c \to \Xi^- K^- \pi^+ \pi^+$
- Mass in agreement with previous data (ARGUS, CLEO, E687-FOCUS, WA89)

$$\frac{BR(\Omega_c \to \Omega^- \pi^+ \pi^0)}{BR(\Omega_c \to \Omega^- \pi^+)} = 1.27 \pm 0.31 \pm 0.11$$

$$\frac{BR(\Omega_c \to \Omega^- 2\pi^+ \pi^-)}{BR(\Omega_c \to \Omega^- \pi^+)} = 0.28 \pm 0.09 \pm 0.01$$

$$\frac{BR(\Omega_c \to \Xi^- K^- 2\pi^+)}{BR(\Omega_c \to \Omega^- \pi^+)} = 0.46 \pm 0.13 \pm 0.03$$



Inclusive data on $e^+e^- \to \Omega_c^* X$

- $L = 230.7$ fb^{-1}
- Decay: $\Omega_c^* \to \Omega_c\gamma$
  - a) $\Omega_c \to \Omega^-\pi^+$
  - b) $\Omega_c \to \Omega^-\pi^+\pi^0$
  - c) $\Omega_c \to \Omega^-\pi^+\pi^+\pi^-$
  - d) $\Omega_c \to \Xi^- K^-\pi^+\pi^+$
- ***css*** **baryon with $J^P = 3/2^+$**

$$M_{\Omega_c^*} - M_{\Omega_c} = (70.8 \pm 1.0 \pm 1.1)\ \text{MeV/c}^2$$

$$\frac{\sigma(e^+e^- \to \Omega_c^* X)}{\sigma(e^+e^- \to \Omega_c X)} = 1.01 \pm 0.23 \pm 0.11$$

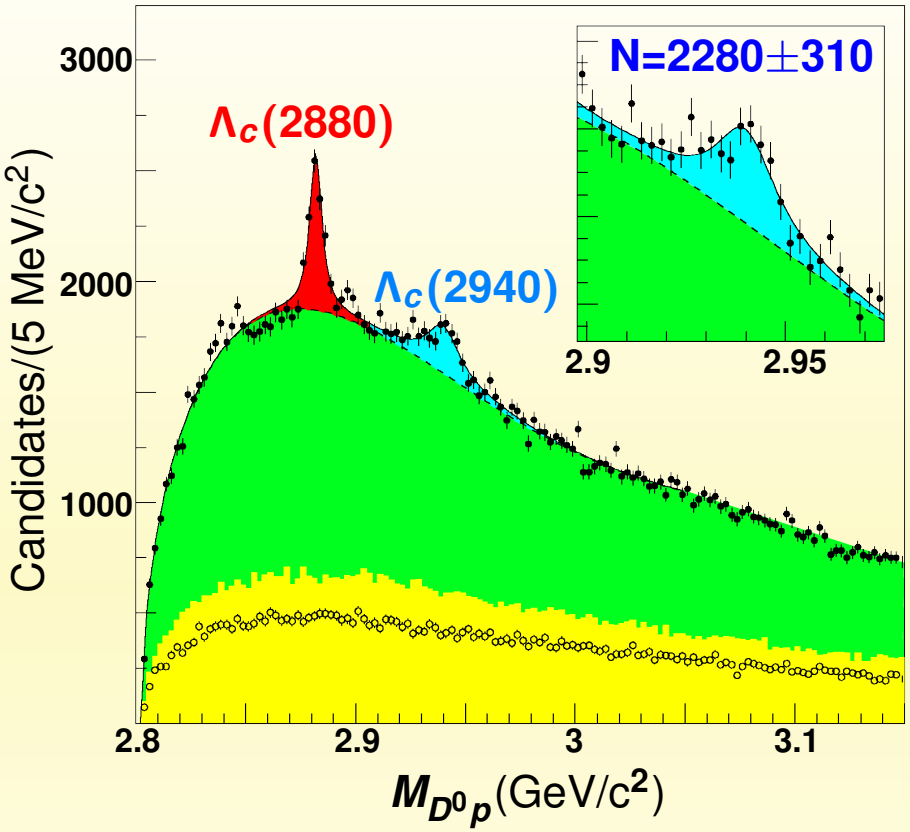
From Ω_c sidebands

Background

Signal + background

$\Lambda_c(2940)$

PRL98, 012001



- ○ Wrong sign $\overline{D^0}p$
- From D^0 sidebands
- Combinatorial background
- $\Lambda_c(2880)$
- $\Lambda_c(2940)$

Inclusive data on $e^+e^- \to D^0 pX$

- $L = 287\ \text{fb}^{-1}$
- No signal in D^+p

$\Downarrow$

isospin=0 $\Rightarrow$ Λ_c not Σ_c

- *udc* baryon

$\Lambda_c(2880)$

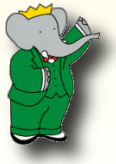
$M = (2881.9 \pm 0.1 \pm 0.5)\ \text{MeV}/c^2$

$\Gamma = (5.8 \pm 1.5 \pm 1.1)\ \text{MeV}$

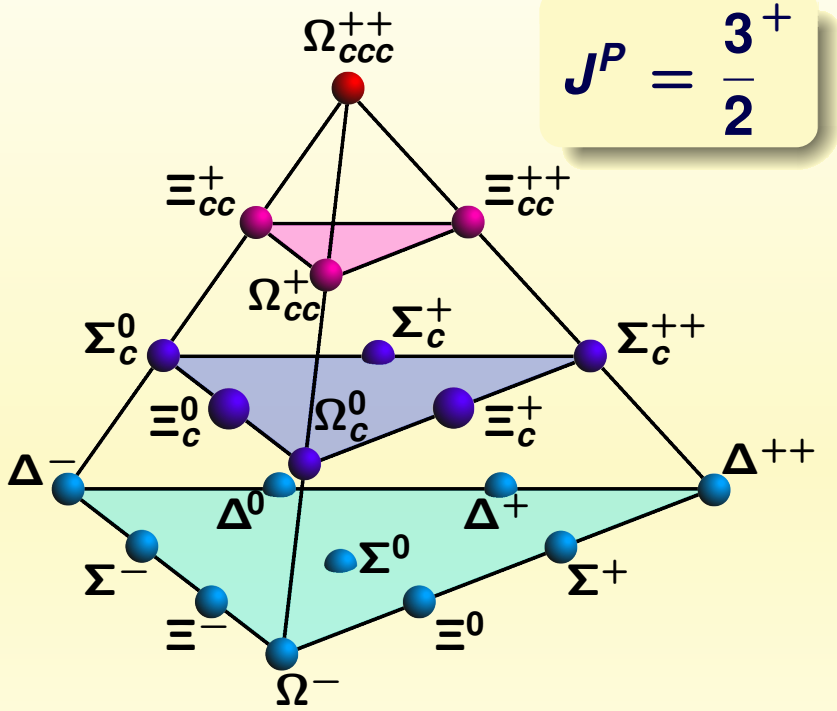
$\Lambda_c(2940)$

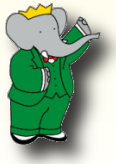
$M = (2939.8 \pm 1.3 \pm 1.0)\ \text{MeV}/c^2$

$\Gamma = (17.5 \pm 5.2 \pm 5.9)\ \text{MeV}$



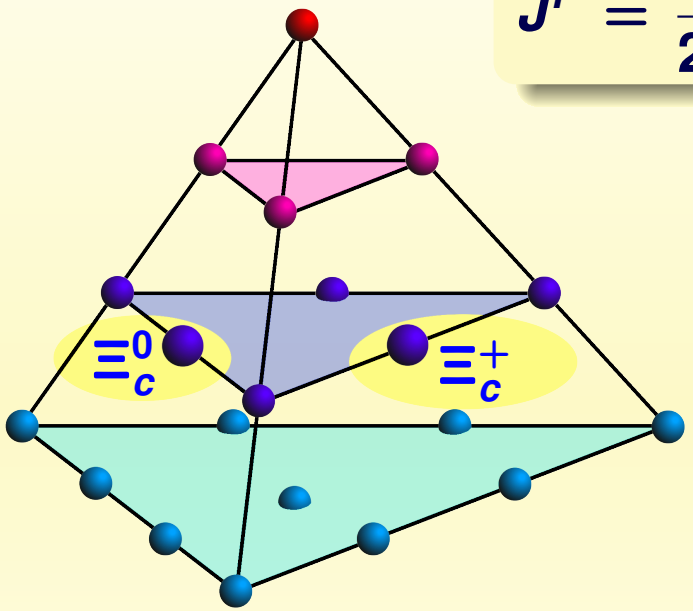
$$J^P = \frac{3}{2}^+$$

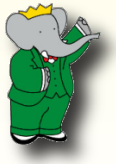

Ω_{ccc}^{++}
Ξ_{cc}^{+}
Ξ_{cc}^{++}
Ω_{cc}^{+}
Σ_c^{0}
Σ_c^{+}
Σ_c^{++}
Ξ_c^{0}
Ω_c^{0}
Ξ_c^{+}
Δ^{-}
Δ^{++}
Δ^{0}
Δ^{+}
Σ^{-}
Σ^{0}
Σ^{+}
Ξ^{-}
Ξ^{0}
Ω^{-}

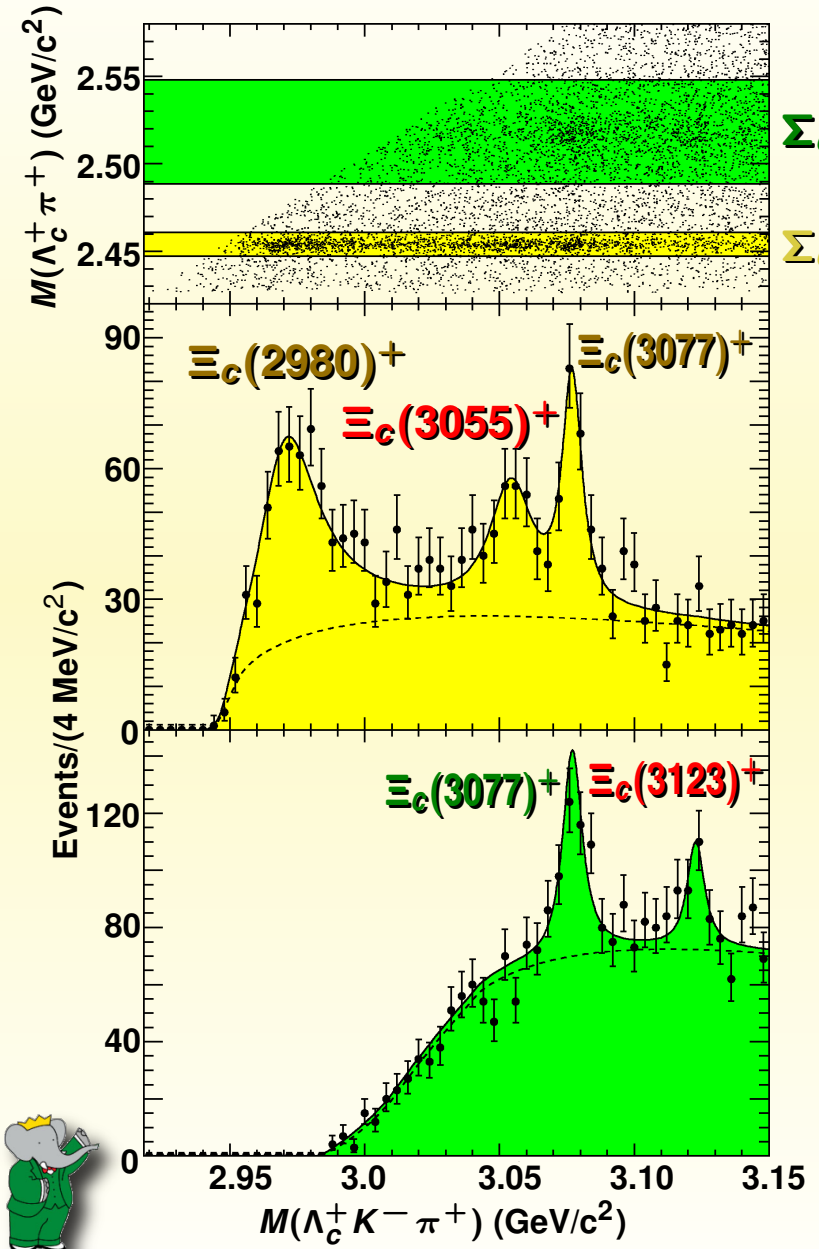


- Inclusive data on $e^+e^- \to \Lambda_c^+ K(n\pi)X$
- $L = 384$ fb^{-1}
- Excited charm-strange baryons
  - $\Xi_c^+(usc)$
  - $\Xi_c^0(dsc)$
- Six samples studied:
  - $\Xi_c^{*+} \to \Lambda_c^+ K_S$
  - $\Xi_c^{*0} \to \Lambda_c^+ K^-$
  - $\Xi_c^{*0} \to \Lambda_c^+ K_S \pi^-$ **Main signal**
  - $\Xi_c^{*+} \to \Lambda_c^+ K^- \pi^+$ **Main signal**
  - $\Xi_c^{*+} \to \Lambda_c^+ K_S \pi^+ \pi^-$
  - $\Xi_c^{*0} \to \Lambda_c^+ K^- \pi^- \pi^+$

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







First evidences

- $\Xi_c(3055)^+ \to \Sigma_c(2455)^{++} K^-$
  - $\to \Lambda_c^+ \pi^+$
- $\Xi_c(3123)^+ \to \Sigma_c(2520)^{++} K^-$
  - $\to \Lambda_c^+ \pi^+$

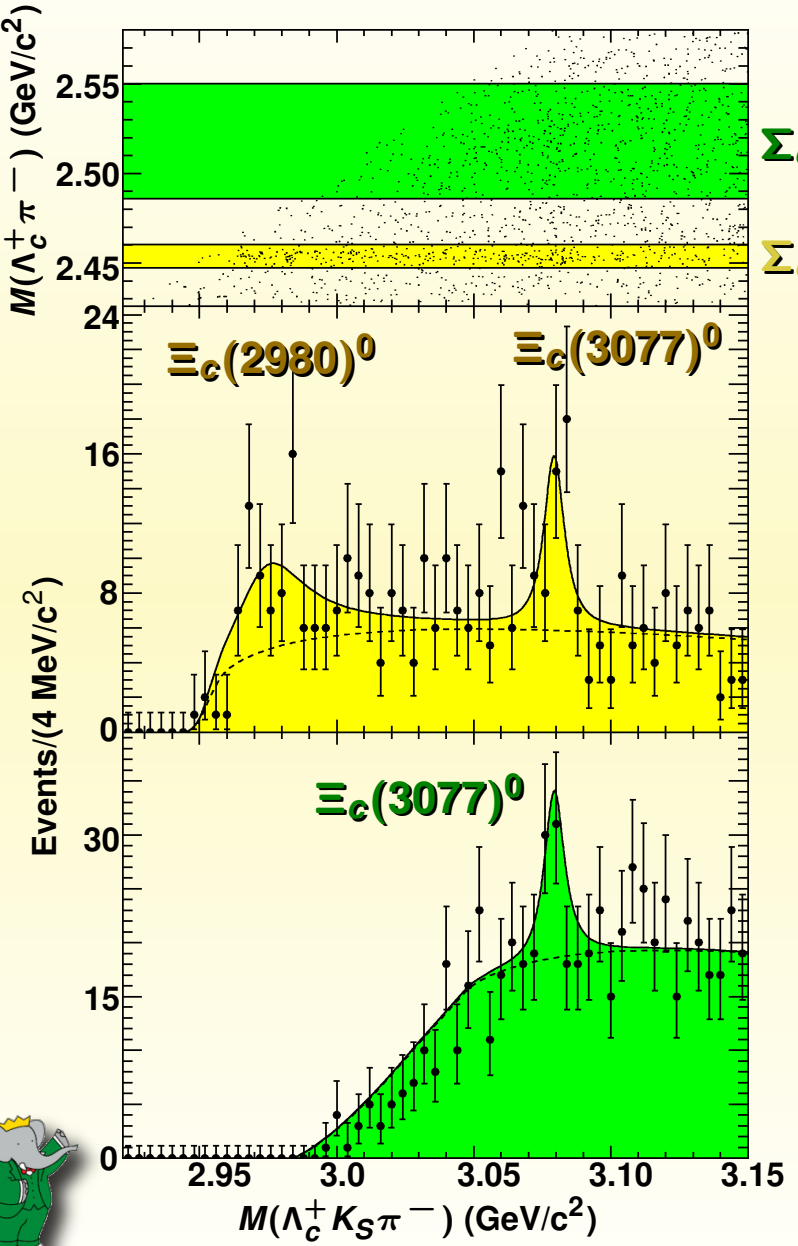
	$\Xi_c(3055)^+$	$\Xi_c(3123)^+$
M (MeV/c^2)	$3054.2 \pm 1.3 \pm 0.5$	$3122.9 \pm 1.3 \pm 0.3$
Γ (MeV)	$17 \pm 6 \pm 11$	$4.4 \pm 3.4 \pm 1.7$
Yield	$218 \pm 53 \pm 79$	$101 \pm 34 \pm 9$
Significance	$6.4\ \sigma$	$3.6\ \sigma$

Mass of $\Xi_c(2980)^+$

BABAR : $2969.3 \pm 2.2 \pm 1.7$ MeV/c^2

BELLE† : $2978.5 \pm 2.1 \pm 2.0$ MeV/c^2

† PRL97, 162001



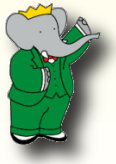
No evidence for neutral $\Xi_c(3055)^0$ and $\Xi_c(3123)^0$

Cross sections

Ξ_c \ $\sigma(y)^\dagger$	$\sigma(\Lambda_c^+ K^- \pi^+)$	$\sigma(\Lambda_c^+ K_S \pi^-)$
$\Xi_c(2980)$	$11.8 \pm 3.4 \pm 2.2$ fb	< 15 fb
$\Xi_c(3055)$	$2.2 \pm 1.2 \pm 0.7$ fb	< 7 fb
$\Xi_c(3077)$	$8.1 \pm 1.2 \pm 0.8$ fb	$6.2 \pm 2.1 \pm 1.5$ fb
$\Xi_c(3123)$	$1.6 \pm 0.6 \pm 0.2$ fb	< 1.4 fb

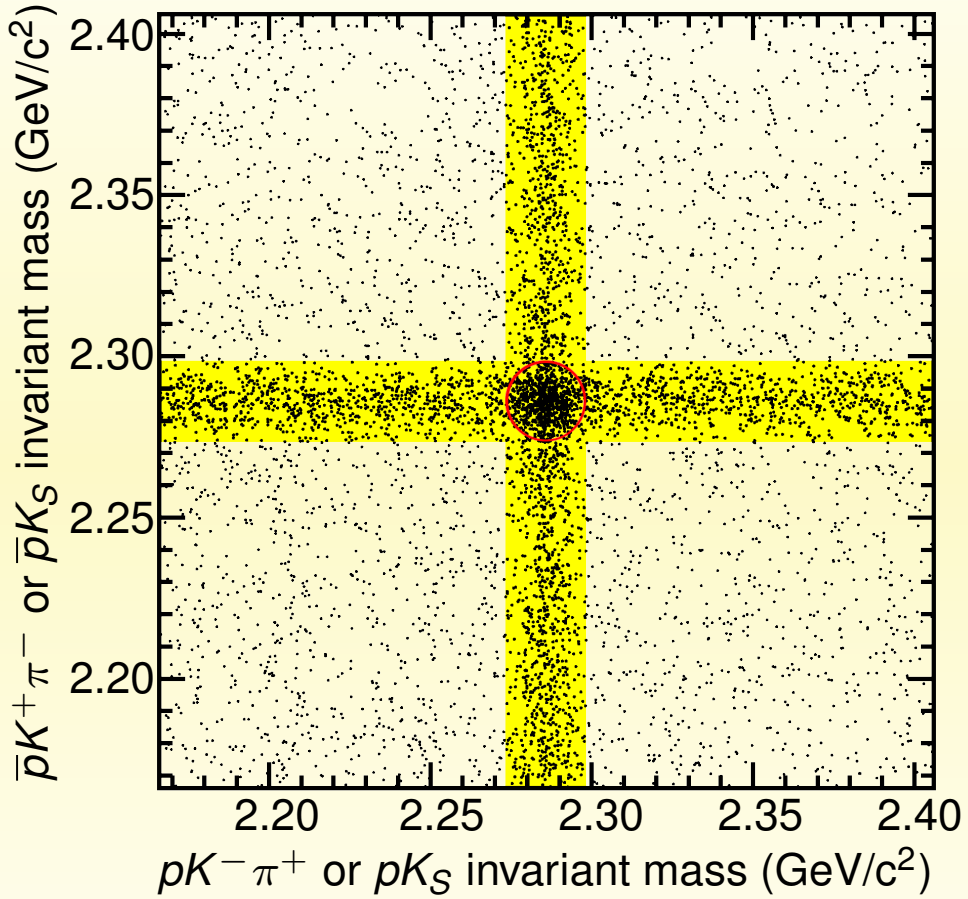
$^\dagger \sigma(y) \equiv \sigma(e^+e^- \to \Xi_c X) \mathrm{BR}(\Xi_c \to y) \mathrm{BR}(\Lambda_c^+ \to p K^- \pi^+)$

- Many excited charmed mesons and baryons are produced in jets
- so far, still working on masses, widths, quantum numbers, and branching fractions
  - *B* decays, other expts will be helpful for this
  - Molecules, hybrids, etc. would be very interesting!
- Then we can extract rates vs. spin, etc.
- The other interesting quantities are the *p* spectra
  - See Fabio Anulli talk for Λ_c, Ξ_c (11:45 wed.)
  - Expect more in the future
- In addition to single-particle studies, we can study events with two "common" charmed particles



$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^- X$

BABAR preliminary



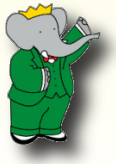
Inclusive data on $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^- X$

- $\Lambda_c^+ \to pK^-\pi^+$ or pK_S + c.c.
- $L = 220$ fb^{-1}
- **919** events in the signal region (◯)
- 245±5 single Λ_c and 25±1 no-Λ_c bkg
- $\Rightarrow$ 641±31 Signal events

For uncorrelated leading charmed hadrons, expect 100-200 "4-baryon" events, $e^+e^- \to \Lambda_c[\bar{p}/\bar{n}]X[p/n]\bar{\Lambda}_c$

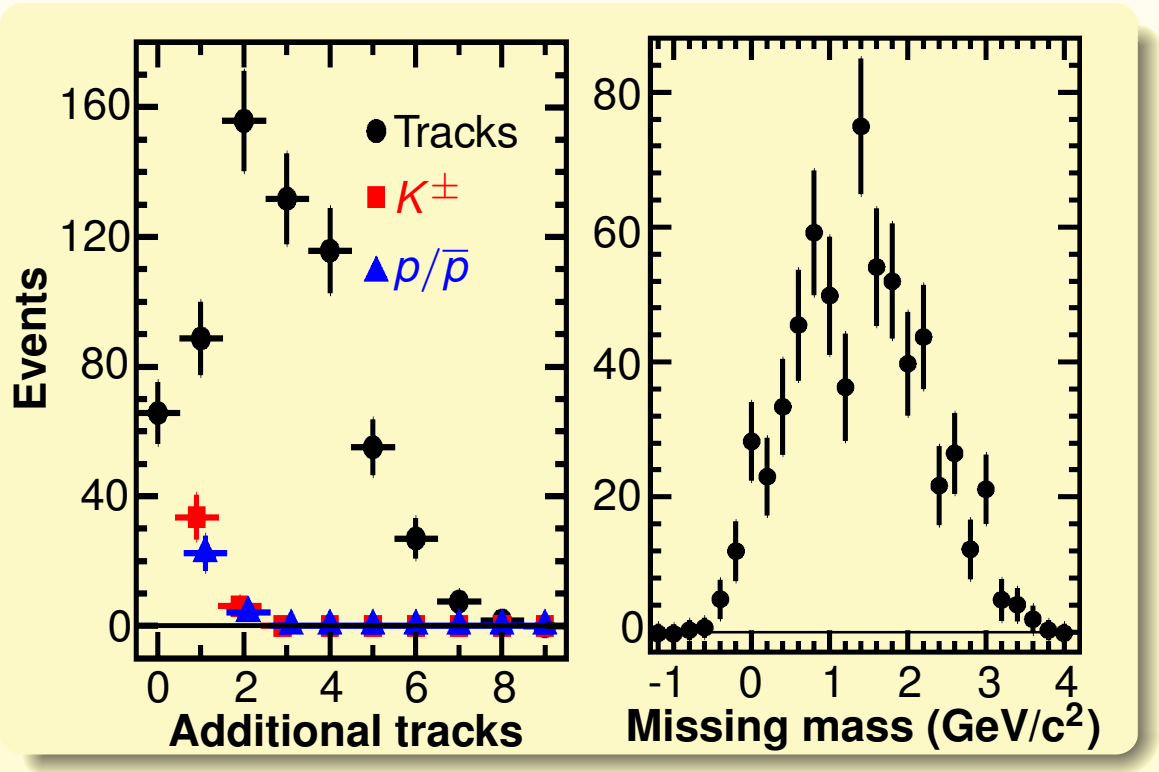
But these might be suppressed since $2M_{\Lambda_c} + 2M_p$ is not $\ll E_{\text{c.m.}}$

Instead we observe an enhancement of ∼4 times, consistent with an observation by CLEO[PRD63, 112003]



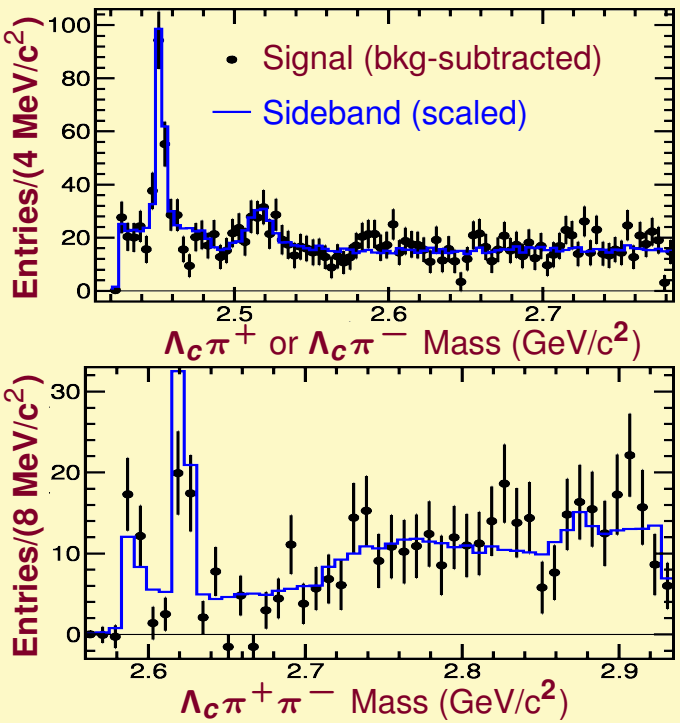
$e^+e^- \to \Lambda_c^+ \overline{\Lambda}_c^- X$

BABAR preliminary



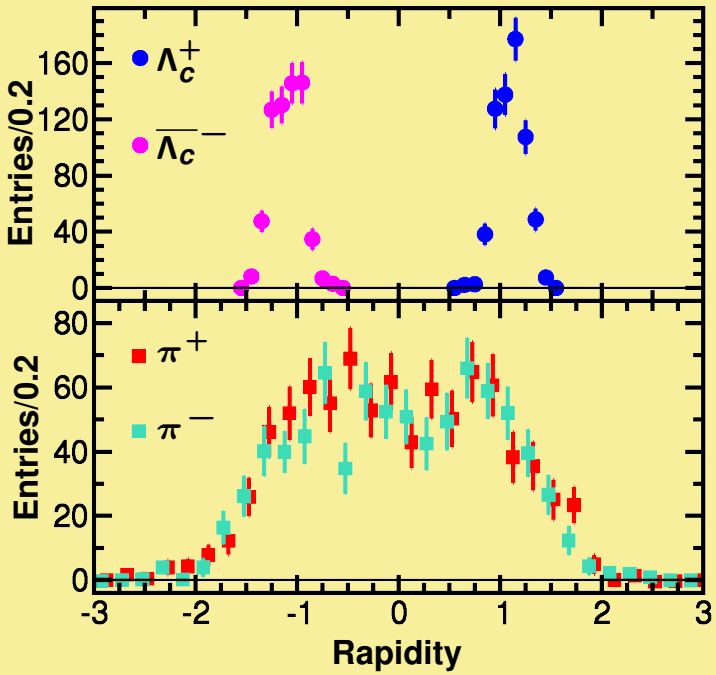
- After full background subtraction
- Several additional tracks, but...
- Very few identified $p/\overline{p}$
- Events with n and $\overline{n}$ would have missing mass > 2 GeV
  - Most of these events have no additional baryons
  - Estimate only 13$\pm$8 4-baryon events $\Rightarrow$ strong suppression

Can these be quasi-2 or quasi-3 events?



- $\Sigma_c^{(*)}$ and Λ_c^* decays are present at relative rates consistent with inclusive events; accounts for 29% of the additional tracks
- 2 events consistent with $e^+e^- \to H_c\overline{H_c}'$
- Study other mass distributions, helicities, opening angles, etc. $\Rightarrow$ no unknown heavier objects
- Also observe very few $K^\pm$, K_S, ρ, K^*,...

Many distributions studied All look like "normal" jetty events



- Λ_c^+ rapidity always > 0
- Correcting for decays, efficiency, there are 2.6 ± 0.3 $\pi^\pm$ per event "between" the c-baryon and $\overline{c}$-baryon
- Missing mass, energy consistent with 1.3 π^0 also

"Long-range" baryon number correlation at sufficiently low energy

HERWIG

no such events produced
4-baryon events suppressed by 40%

PYTHIA

4-baryon events suppressed by 20%
2-body $H_c\bar{H}_c'$, 3-body $H_cM\bar{H}_c'$ present at low rates

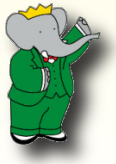
UCLA

4-baryon events suppressed by 95%

- produces events with these qualitative features and the rate is enhanced (too much)
- there are very few kaons or vector mesons
- the intermediate meson multiplicity distribution is broad, but peaks at 1 with only 1.8 on average

Questions

- What is the underlying mechanism?
- How does this depend on $E_{c.m.}$, baryon mass?
- Can we see baryons separated by > 2 units of rapidity and 4 mesons in higher energy jets?



Summary

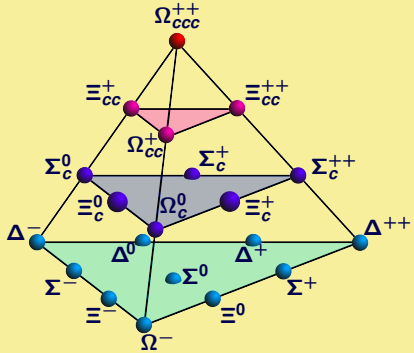
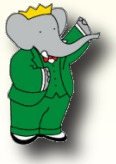
Charmed Mesons

- Improved measurements for $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$ parameters, signatures of $KD^{(*)}$ molecular states?
- Observation of **new states** $D_{sj}^{*}(2860)$ and $X(2690)$

Charmed Baryons

- New charmed baryons discovered:

Ω_c^* $\Lambda_c(2940)$ $\Xi_c(3055)$ $\Xi_c(3123)$



- Λ_c^+-$\overline{\Lambda}_c^-$ production, measured in the $c\bar{c}$ continuum, shows an important correlation between baryon and antibaryon