First observation and measurements of $\Lambda_c(2765)^+$, $\Lambda_c(2880)^+$, $\Lambda_c(2940)^+$ and studies of $\Lambda_c(2880)^+$ spin-parity – contents analysis

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`arXiv:hep-ex/0603052`,
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Introduction

Checks for theoretical predictions:

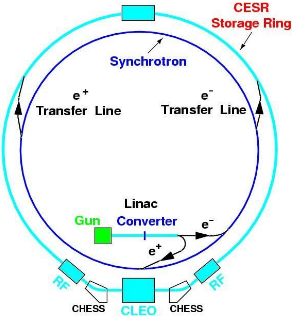
- Decay channels,
- Masses and widths of resonances,
- Quantum numbers (spin-parity).

This information is very useful for construction and tuning of phenomenological models. It may also reveal more CP asymmetry cases.

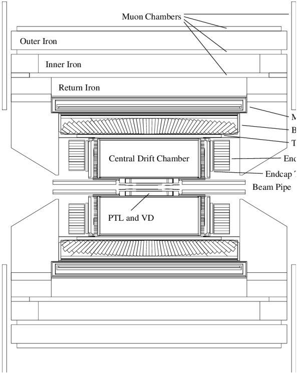
CLEO detector

Located at Cornell Electron Storage Ring (Cornell Univ., USA)

Real photo



Scheme



Detector

ee annihilation at $\Upsilon(4S)$

Drift chamber

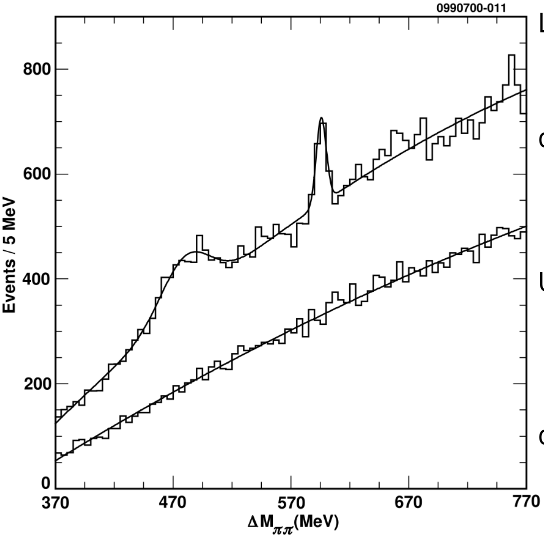
EM calorimeter

Time-of-flight

Data selection (CLEO)

- Λ_c^+ reconstructed in 15 modes: combinations of p, K, π, Λ, Ξ, Σ, ϕ. Mass requirement: within 1.6σ of $m(\Lambda_c^+)_{\text{table}}$.
- Background suppression: cuts on $x_p = p/p_{\max}$.
  $p_{\max}$ is the max. the momentum can be given beam energy.
- $x_p > 0.5$ rules out the largest comb. bkg. from B-mesons. Applied to Λ_c^+ candidates.
- Λ_c^+ then combined with two pions: $\Lambda_c^+\pi^+\pi^-$.
- Further requirement $x_p > 0.7$ for $\Lambda_c^+\pi^+\pi^-$ suggested by kinematics and existing results.

$\Delta M(\pi\pi) = M(\Lambda_c^+\pi\pi) - M(\Lambda_c^+)$ fit



Lower

$\Delta M_{\pi\pi} = 480 \pm 3$ MeV

$\sigma = 21 \pm 3$ MeV

or

$\Gamma \approx 50$ MeV

Upper

$\Delta M_{\pi\pi} = 595.8 \pm 0.8$ MeV ± 2 MeV

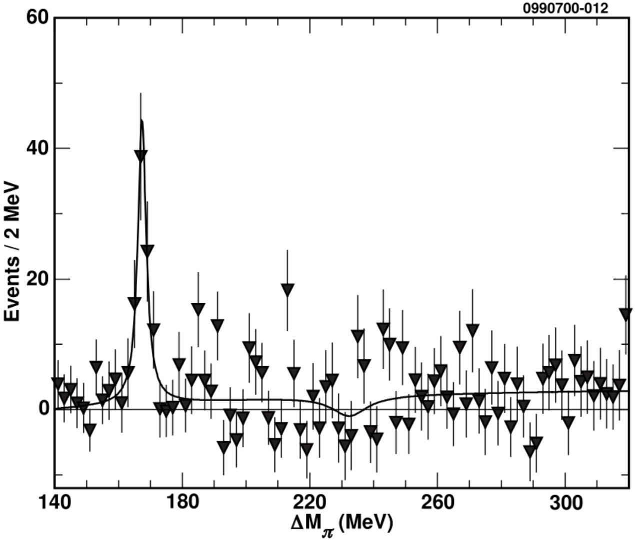
$\sigma = 4.2 \pm 0.7$ MeV

or

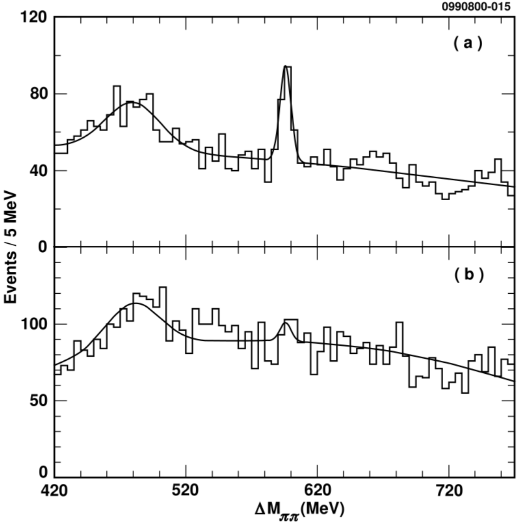
$\Gamma = 4 \pm 2 \pm 2$ MeV

Syst. dominated by resolution for Γ, momentum measurement and fitting for mass.

$\Delta M(\pi) = M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ spectrum



$\Delta M(\pi\pi)$ spectrum from parts of $\Delta M(\pi)$



$\Sigma_c(2455)$

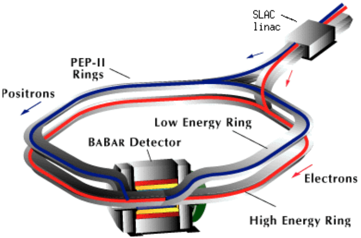
$\Sigma_c(2520)$

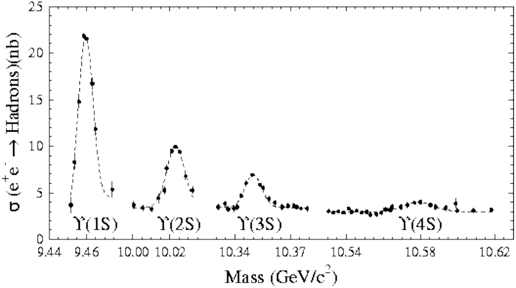
Quark states of observed resonances

- $\Lambda_c(2880)^+$ decays into $\Sigma_c(2455)\pi$ and $\Lambda_c^+\pi^+\pi^-$ directly.
- $\Lambda_c(2765)^+$ possibly decays via all three modes $\Sigma_c(2455)\pi$, $\Sigma_c(2520)\pi$, $\Lambda_c^+\pi^+\pi^-$.
- Based on HQET and conservation of both J^P and J^P_{diquark}:
- Upper ($\Lambda_c(2880)^+$):
  $J^P = 1/2^-$, $J^P_{\text{diquark}} = 0^-$, $L = 1$
  or a mixture with $J^P_{\text{diquark}} = 1^-$, $L = 0$
- Lower ($\Lambda_c(2765)^+$): very unclear. May even be two resonances 30 MeV apart.

BaBar detector

Located at PEP-II at SLAC (Stanford University, USA)





ee annihilation at $\Upsilon(4S)$

Vertex tracker

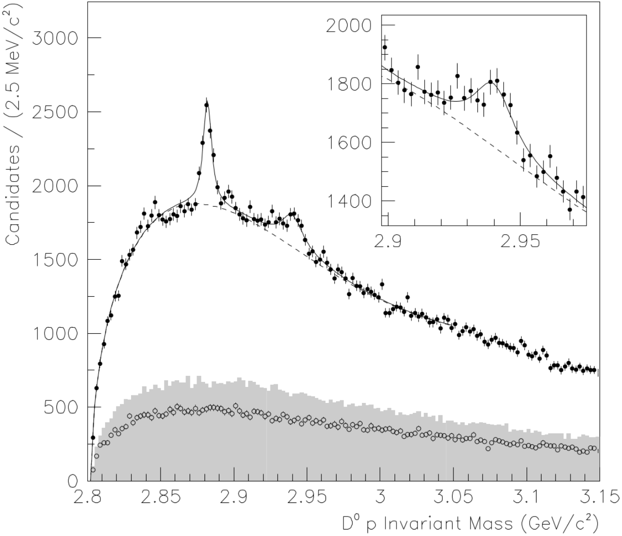
Drift chamber

Cherenkov detector

Data selection (BaBar)

- Inclusive $D^0 p$ spectrum investigated.
- D^0 reconstructed in $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ (fit to a common vertex).
- p added using a vertex fit.
- Additional requirements:
  $\Delta m = m(D^0)_{\text{reco}} - m(D^0)_{\text{table}}$,
  p^* – c.m. momentum of $D^0 p$ (excludes B-meson bkg),
  $\cos\theta$ between p and ee system,
  Based on simulation to maximize significance.

$D^0 p$ spectrum and fit

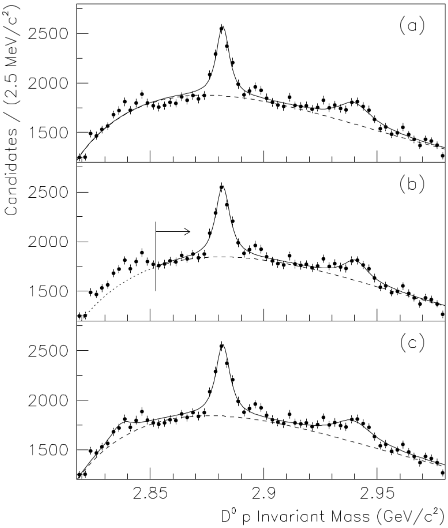


D^0 sidebands in gray, $\overline{D}^0$ wrong charge in open circles: no structures there.

$\Lambda_c(2880)^+$:
$m = 2881.9 \pm 0.1$ MeV
$\Gamma = 5.8 \pm 1.5$ MeV

$\Lambda_c(2940)^+$:
$m = 2939.8 \pm 1.3$ MeV
$\Gamma = 17.5 \pm 5.2$ MeV

D^0p spectrum: structure at the low end



$\Lambda_c(2940)^+$:

0.5 MeV lower mass

$\Gamma = 12.5$ MeV

Assigned as syst. errors.

$\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ results

- Systematics come from fit model and the knowledge of $m(D^0)_{\text{table}}$.
- $\Lambda_c(2880)^+$:

$$m = 2881.9 \pm 0.1 \pm 0.5 \text{ MeV}$$

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

- $\Lambda_c(2940)^+$

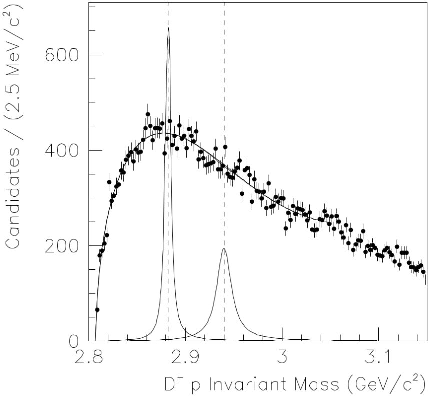
$$m = 2939.8 \pm 1.3 \pm 1.0 \text{ MeV}$$

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

- $\dfrac{\sigma\left(\Lambda_c(2940)^+\right)\,\mathcal{B}\left(\Lambda_c(2940)^+ \to D^0 p\right)}{\sigma\left(\Lambda_c(2880)^+\right)\,\mathcal{B}\left(\Lambda_c(2880)^+ \to D^0 p\right)} = 0.81 \pm 0.13 \pm 0.35$

Tests for $\Lambda_c(2940)^+$

- Not coming from K or π misidentified as p: such spectra exhibit no peaks.
- Not coming from a heavier narrow Λ_c^{*+} decaying into D^*p: no peaks in D^*p spectra.
- Not coming from a heavier Λ_c^{*+} decaying into $D^0\Sigma^+$: kinematics of $D^0\Sigma^+$ are different.
- $\Lambda_c(2940)^+$ is not a Σ_c^{*+}: no doubly-charged state in D^+p.

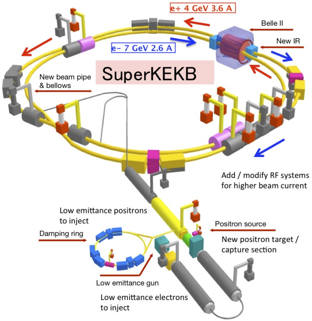


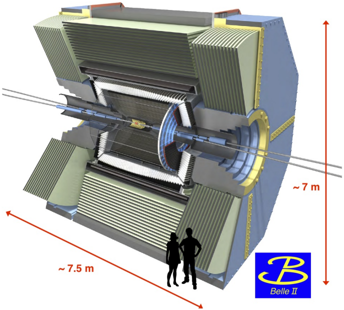
Conclusions about $\Lambda_c(2880)^+$, $\Lambda_c(2940)^+$

- First observation of $D^0 p$ decay mode.
  (and, to this day, the only one)
- $\Lambda_c(2940)^+$ not observed in $\Lambda_c^+ \pi^+ \pi^-$ by CLEO.
  Why is $D^0 p$ favored in spite of phase space?
- $\Lambda_c(2880)^+$ consistent with CLEO measurement.

Belle detector

Located at KEKB at KEK (High Energy Accelerator Research Organization, Japan)





ee annihilation at $\Upsilon(4S)$

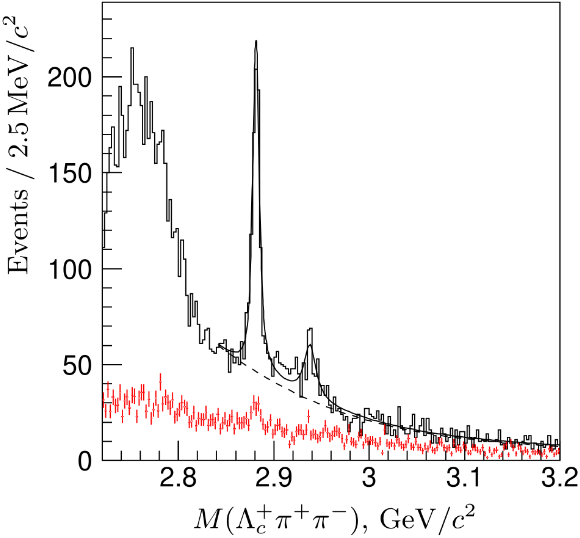
Vertex detector Drift chamber Cherenkov detector

Time-of-flight counters Scintillator

Data selection (Belle)

- Λ_c^+ reconstructed in $\Lambda_c^+ \to pK^-\pi^+$.
- Λ_c^+ mass required to be within 1.6σ of existing measurements.
- Particle identification applied.
- Cut on $x_p > 0.7$ for $\Lambda_c^+\pi^+\pi^-$ candidates.
- For mass fits, $\Lambda_c^+\pi$ mass cut to $\Sigma_c(2455)$ region.
  This reduces the signal, but heavily suppresses the bkg.

$\Lambda_c^+\pi^+\pi^-$ spectrum and fit



$\Lambda_c(2880)^+$:

$m = 2881.2 \pm 0.2 \pm 0.4$ MeV

$\Gamma = 5.8 \pm 0.7 \pm 1.1$ MeV

$\Lambda_c(2940)^+$:

$m = 2938.0 \pm 1.3^{+2.0}_{-4.0}$ MeV

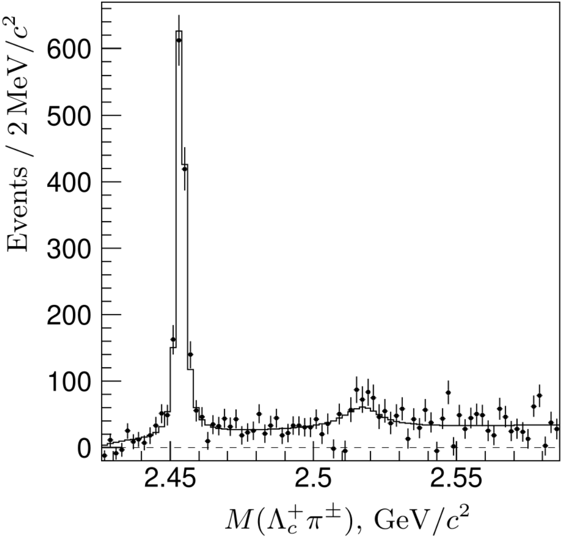
$\Gamma = 13^{+8+27}_{-5-7}$ MeV

$\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ measurements systematics

- 4th-order polynomial instead of 3rd.
  Inverse 3rd-order polynomial.
- Include $\Lambda_c(2765)^+$ region in the fit: Breit-Wigner.
- Selection requirements.
- Uncertainty in detector resolution.
- Poor fit quality between 2880 and 2940 MeV.

Main sources: $\Lambda_c(2765)^+$ and region between 2880 and 2940 MeV.

$\Lambda_c(2880)^+$ yields in $\Lambda_c^+\pi$ mass bins



$\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ models are fixed in $\Lambda_c^+\pi^+\pi^-$ fits.

Non-res. component shape in $\Lambda_c^+\pi$ is taken from simulation.

$\Sigma_c(2455)$ parameters floated.

$\Sigma_c(2520)$ parameters fixed.

$\Lambda_c(2880)^+$ branching ratios systematics

$$\frac{\Gamma(\Sigma_c(2455)\pi)}{\Gamma(\Lambda_c^+\pi^+\pi^-)} = 0.404 \pm 0.021 \pm 0.014, \quad \frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Lambda_c^+\pi^+\pi^-)} = 0.091 \pm 0.025 \pm 0.010$$

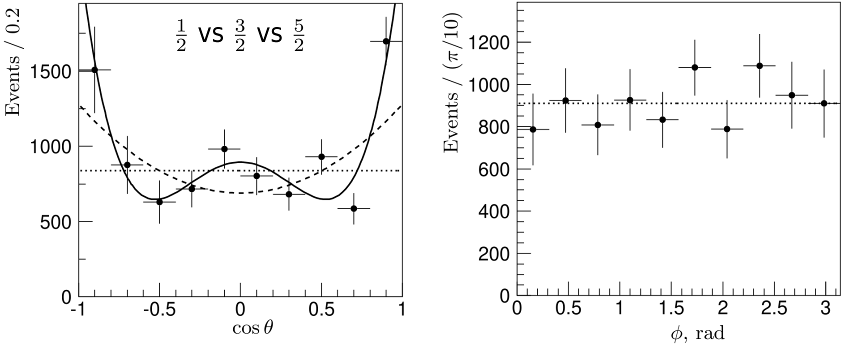
$$\frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)} = 0.225 \pm 0.062 \pm 0.025$$

- Parameters of $\Lambda_c(2880)^+$.
- $\Lambda_c^+\pi^+\pi^-$ fit interval.
- Bkg shape in $\Lambda_c^+\pi^+\pi^-$.
- $\Sigma_c(2520)$ parameters in $\Lambda_c^+\pi$ fit.
- Non-resonant shape in $\Lambda_c^+\pi$ fit:
  2nd-order polynomial with threshold,
  3rd-order polynomial.

$\Lambda_c(2880)^+ \to \Sigma_c\pi$ yields in $\cos\theta$ and $\cos\phi$ bins

θ – between π in $\Lambda_c(2880)^+$ rest frame and $\Lambda_c(2880)^+$ boost.

ϕ – between $ee \to \Lambda_c(2880)^+X$ reaction plane and plane formed by π momentum and $\Lambda_c(2880)^+$ boost.



$$\frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)} = 1.4$$ for $\frac{5}{2}^-$ and 0.23–0.36 for $\frac{5}{2}^+$. Measured 0.225 ± 0.067

Results of $\Lambda_c(2880)^+$ spin measurement

- Spin $\frac{5}{2}^+$ hypothesis strongly favored.
- Spin $\frac{1}{2}^+$ hypothesis exclusion level: 5.5 sigma.
- Spin $\frac{3}{2}^+$ hypothesis exclusion level: 4.5 sigma.
- Spin-parity $\frac{5}{2}^+$ is favored.
- $\Lambda_c(2880)^+$ belongs to the sequence

$$\Lambda_c^+ \left(\frac{1}{2}^+\right), \Lambda_c(2625)^+ \left(\frac{3}{2}^-\right), \Lambda_c(2880)^+ \left(\frac{5}{2}^+\right).$$