Charm Baryon Spectroscopy at CDF

Study of $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$ and $\Sigma_c(2520)$ Baryons

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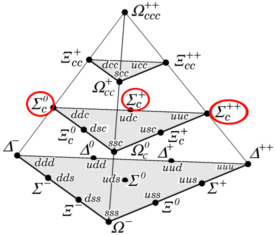
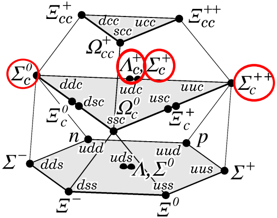
July 23, 2010

ICHEP 2010

Charm Baryons



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

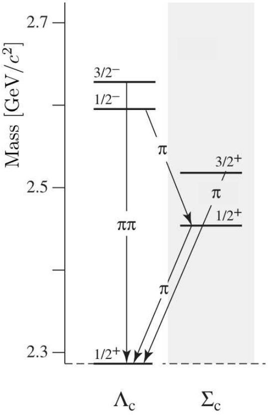


$J^P = \frac{1}{2}^+$

- Λ_c^+ ($J^P = \frac{1}{2}^+$) charm baryon with smallest mass $\Rightarrow$ weak decay
- $\Sigma_c(2455)$ ($J^P = \frac{1}{2}^+$), $\Sigma_c(2520)$ ($J^P = \frac{3}{2}^+$)
  - Λ_c^+ spin excitations: spin-1 light diquark
  - isospin triplets Σ_c^0, Σ_c^+, Σ_c^{++}
  - strong decay to $\Lambda_c^+ \pi^{-,+,0}$

Λ_c^+ Orbital Excitations ($l = 1$)

$$\Lambda_c(2595)^+ \; (J^P = \tfrac{1}{2}^-) \text{ and } \Lambda_c(2625)^+ \; (J^P = \tfrac{3}{2}^-)$$



- isospin singlets ⇒ decay to $\Lambda_c^+ \pi^+ \pi^-$
- nonresonant decays via *P*-wave (parity conservation in strong interaction)
- resonant decays $\Lambda_c(2595) \to \Sigma_c(2455)\,\pi$ via *S*-wave
- resonant decays $\Lambda_c(2625) \to \Sigma_c(2455)\,\pi$ via *D*-wave (angular momentum and parity conservation)
- resonant decays to $\Sigma_c(2520)\,\pi$ kinematically inapproachable

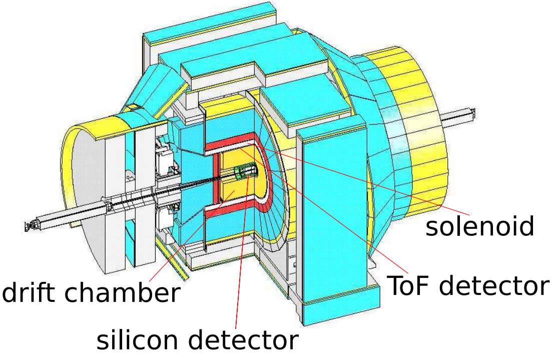
CDF Experiment at Tevatron

Tevatron

- p-$\bar{p}$ collider
- $\sqrt{s} = 1.96\,\mathrm{TeV}$

CDF II

- multipurpose detector
- excellent tracking and mass resolution
- trigger on displaced tracks for selection of secondary vertex decays

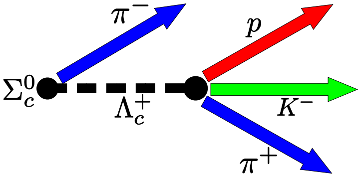


Motivations

- charmed baryon system testing ground for heavy quark symmetry
  - rich mass spectrum
  - relatively narrow widths of the resonances
- improvement of previous mass and decay width measurements of $\Sigma_c(2455)^{0,++}$, $\Sigma_c(2520)^{0,++}$, $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$
- proper inclusion of kinematical threshold effects in $\Lambda_c(2595)^+ \rightarrow \Sigma_c(2455)^{0,++}\,\pi^{+,-}$
- direct experimental determination of pion coupling constant h_2 in chiral Lagrangian
  - knowledge of h_2 provides information about other excited charm and bottom baryons
  - up to now calculated using measured $\Gamma(\Lambda_c(2595)^+)$

Selection Method

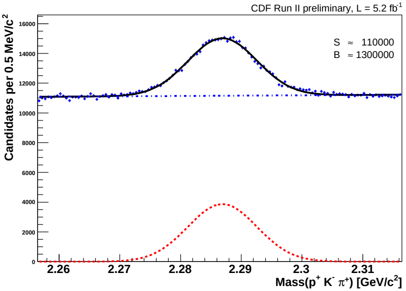
- Hadronic Trigger requires two displaced tracks with $p_t > 2\,\mathrm{GeV}/c$
- application of neural networks (NeuroBayes)
  - $\Lambda_c^+ \rightarrow p^+ \, K^- \, \pi^+$
    lifetime, vertex fit, particle identification, Dalitz structure
  - $\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \, \pi^{-,+}$, $\Lambda_c^{*+} \rightarrow \Lambda_c^+ \, \pi^+ \, \pi^-$
    Λ_c^+ network output, vertex fits



Network Trainings

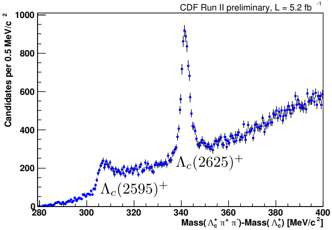
- trainings solely based upon real data by means of ${}_s\mathcal{P}lot$ weights
  $\Rightarrow$ independent of simulated events
- ${}_s\mathcal{P}lot$ technique corresponds to advanced sideband subtraction
  Nucl. Instr. Meth.A 555, 356-369
- invariant mass as discriminating variable between signal and background $\rightarrow$ requires significant signal in mass spectrum

candidates used for Λ_c^+ training:

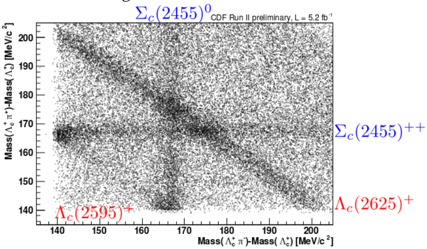


Resulting Spectra

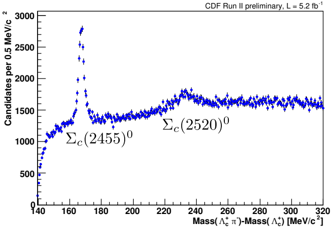
$$\Lambda_c^{*+} \to \Lambda_c^+ \pi^+ \pi^-$$



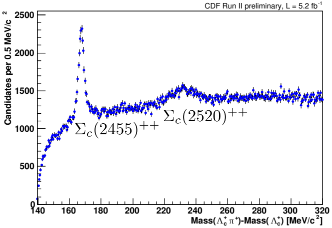
$$\Lambda_c^{*+} \to \Sigma_c^{0,++} \pi^{+,-}$$



$$\Sigma_c^0 \to \Lambda_c^+ \pi^-$$



$$\Sigma_c^{++} \to \Lambda_c^+ \pi^+$$



Detector Resolutions

- determined from Monte Carlo simulations
- modeled by triple-Gaussian functions

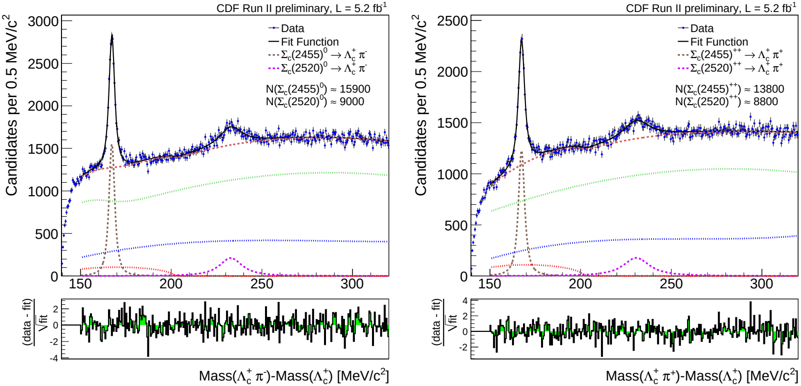
	$\Sigma_c(2455)$	$\Sigma_c(2520)$	$\Lambda_c(2595)$	$\Lambda_c(2625)$
$\bar{\sigma}[\mathrm{MeV}/c^2]$	1.6	2.5	1.8	2.4

- reference decays for validation:
  - $D^*(2010)^+ \to D^0\,\pi^+$
  - $\psi(2S) \to J/\psi\,\pi^+\,\pi^-$

Fit Strategy

- binned maximum likelihood method
- signals:
  - convolutions of nonrelativistic Breit-Wigner functions with detector resolutions
  - $\Lambda_c(2595)^+$: consideration of kinematical threshold effects in resonant decays to $\Sigma_c(2455)^{0,++}\,\pi^{+,-}$
- several background constituents:
  - combinatorial background without real Λ_c^+
    $\rightarrow$ determined from Λ_c^+ mass sidebands
  - real Λ_c^+ with random tracks
  - contaminations from Λ_c^* feed-down in Σ_c spectra and Σ_c with random track in Λ_c^* spectrum
    $\rightarrow$ examination of two-body line shapes from three-body decays

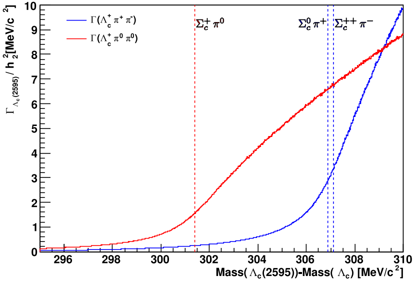
$\Sigma_c(2455)^{0,++}$ and $\Sigma_c(2520)^{0,++}$ Fits



- combinatorial background without real Λ_c^+
- real Λ_c^+ with random track
- feed-down from $\Lambda_c(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$

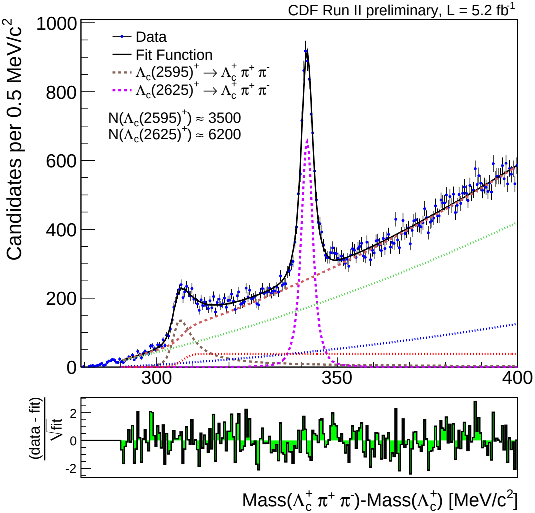
$\Lambda_c(2595)^+$ Line Shape

- $\Lambda_c(2595)^+ \to \Sigma_c(2455)^{0,++}\,\pi^{+,-}$ right at kinematical threshold
- $\Rightarrow$ Breit-Wigner shape with mass-dependent width
  - $\frac{\mathrm{d}N}{\mathrm{d}\Delta m} \propto \frac{\Gamma(\Lambda_c^+\,\pi^+\,\pi^-)}{(\Delta m - \Delta m_{\Lambda_c(2595)})^2 + (\Gamma(\Lambda_c^+\,\pi^+\,\pi^-) + \Gamma(\Lambda_c^+\,\pi^0\,\pi^0))^2/4}$
  - numerator: partial decay width of examined channel
  - denominator: sum over all decay channels



- Blechman *et al.*: Threshold effects in excited charmed baryon decays, *Phys. Rev. D 67, 074033*
- h_2: pion coupling constant in $\Lambda_c(2595) \to \Sigma_c(2455)\,\pi$ $\to$ can be determined from data

$\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ Fits



- combinatorial background without real Λ_c^+
- real Λ_c^+ with two random tracks
- $\Sigma_c^{0,++}$ with random track
- CLEO:
  112 $\Lambda_c(2595)^+$ and
  245 $\Lambda_c(2625)^+$ events

Systematic Uncertainties

- detector resolutions:
  uncertainties on the Monte Carlo simulations
- overall mass scale:
  magnetic field and energy loss uncertainties in momentum scale calibration
- fit models
- external input for $\Lambda_c(2595)^+$ signal shape:
  uncertainties on PDG values of $\Sigma_c(2455)$ mass differences and decay widths

Systematic Uncertainties

Source	$\Delta m(\Sigma_c(2455)^0)$	$\Gamma(\Sigma_c(2455)^0)$	$\Delta m(\Sigma_c(2520)^0)$	$\Gamma(\Sigma_c(2520)^0)$
Resolution	-	$0.45\,\mathrm{MeV}/c^2$	-	$0.70\,\mathrm{MeV}/c^2$
Mass Scale	$0.12\,\mathrm{MeV}/c^2$	$0.20\,\mathrm{MeV}/c^2$	$0.12\,\mathrm{MeV}/c^2$	$0.20\,\mathrm{MeV}/c^2$
Fit Model	$0.02\,\mathrm{MeV}/c^2$	-	$0.11\,\mathrm{MeV}/c^2$	$1.16\,\mathrm{MeV}/c^2$
Sum	$0.12\,\mathrm{MeV}/c^2$	$0.49\,\mathrm{MeV}/c^2$	$0.16\,\mathrm{MeV}/c^2$	$1.37\,\mathrm{MeV}/c^2$
Statistical	$0.03\,\mathrm{MeV}/c^2$	$0.11\,\mathrm{MeV}/c^2$	$0.43\,\mathrm{MeV}/c^2$	$1.82\,\mathrm{MeV}/c^2$

Source	$\Delta m(\Sigma_c(2455)^{++})$	$\Gamma(\Sigma_c(2455)^{++})$	$\Delta m(\Sigma_c(2520)^{++})$	$\Gamma(\Sigma_c(2520)^{++})$
Resolution	-	$0.40\,\mathrm{MeV}/c^2$	-	$0.69\,\mathrm{MeV}/c^2$
Mass Scale	$0.12\,\mathrm{MeV}/c^2$	$0.20\,\mathrm{MeV}/c^2$	$0.12\,\mathrm{MeV}/c^2$	$0.20\,\mathrm{MeV}/c^2$
Fit Model	$0.02\,\mathrm{MeV}/c^2$	-	$0.11\,\mathrm{MeV}/c^2$	$1.16\,\mathrm{MeV}/c^2$
Sum	$0.12\,\mathrm{MeV}/c^2$	$0.45\,\mathrm{MeV}/c^2$	$0.16\,\mathrm{MeV}/c^2$	$1.36\,\mathrm{MeV}/c^2$
Statistical	$0.04\,\mathrm{MeV}/c^2$	$0.13\,\mathrm{MeV}/c^2$	$0.56\,\mathrm{MeV}/c^2$	$2.12\,\mathrm{MeV}/c^2$

Source	$\Delta m(\Lambda_c(2595)^+)$	h_2^2	$\Gamma(\Lambda_c(2595)^+)$	$\Delta m(\Lambda_c(2625)^+)$
Resolution	$0.06\,\mathrm{MeV}/c^2$	0.03	$0.22\,\mathrm{MeV}/c^2$	-
Mass Scale	$0.12\,\mathrm{MeV}/c^2$	0.03	$0.20\,\mathrm{MeV}/c^2$	$0.12\,\mathrm{MeV}/c^2$
Δm, Γ of $\Sigma_c(2455)$	$0.15\,\mathrm{MeV}/c^2$	0.06	$0.36\,\mathrm{MeV}/c^2$	-
Sum	$0.20\,\mathrm{MeV}/c^2$	0.07	$0.47\,\mathrm{MeV}/c^2$	$0.12\,\mathrm{MeV}/c^2$
Statistical	$0.14\,\mathrm{MeV}/c^2$	0.04	$0.30\,\mathrm{MeV}/c^2$	$0.04\,\mathrm{MeV}/c^2$

Results

analysis provides 12 measurements (PDG values in parentheses):

	$m - m(\Lambda_c^+)[\mathrm{MeV}/c^2]$	$\Gamma[\mathrm{MeV}/c^2]$
$\Sigma_c(2455)^0$	167.28 ± 0.12 (167.30 ± 0.11)	1.65 ± 0.50 (2.2 ± 0.4)
$\Sigma_c(2455)^{++}$	167.44 ± 0.13 (167.56 ± 0.11)	2.34 ± 0.47 (2.23 ± 0.30)
$\Sigma_c(2520)^0$	232.88 ± 0.46 (231.6 ± 0.5)	12.51 ± 2.28 (16.1 ± 2.1)
$\Sigma_c(2520)^{++}$	230.73 ± 0.58 (231.9 ± 0.6)	15.03 ± 2.52 (14.9 ± 1.9)
$\Lambda_c(2595)^+$	305.79 ± 0.24 (308.9 ± 0.6)	2.59 ± 0.56 $(3.6^{+2.0}_{-1.3})$
$\Lambda_c(2625)^+$	341.65 ± 0.13 (341.7 ± 0.6)	$< 0.97(90\% CL)$ $(< 1.9(90\% CL))$

- $h_2^2 = 0.36 \pm 0.08$ (equivalent to $\Gamma(\Lambda_c(2595)^+)$)
- difference in $m(\Lambda_c(2595)^+) - m(\Lambda_c^+)$ due to proper treatment of kinematical threshold effects, data consistent

Summary

- mass difference and decay width measurements of the charmed baryons $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Sigma_c(2455)^{0,++}$, $\Sigma_c(2520)^{0,++}$
- $\Sigma_c^{0,++} \to \Lambda_c^+ \pi^{-,+}$
  $\Lambda_c^{*+} \to \Lambda_c^+ \pi^+ \pi^-$
  with $\Lambda_c^+ \to p^+ K^- \pi^+$
- analysis with highest number of signal events
- proper inclusion of kinematical threshold effects in $\Lambda_c(2595)^+ \to \Sigma_c(2455)^{0,++} \pi^{+,-}$
  - significant smaller measured value of the $\Lambda_c(2595)^+$ mass
  - direct measurement of the pion coupling constant h_2
- after bottom and charm mesons as well as bottom baryons CDF now also studies charm baryons