Measurement of the absolute branching fraction of the inclusive semileptonic Λ_c^+ decay

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Outline

Section 1

Overview

The lowest-lying charmed baryon Λ_c^+ was discovered more than 40 years ago[1][2] , but its decays have not yet been fully mapped out due to the many available modes (about 80 kinds according to PDG2018).

BESIII collaboration measured the absolute branching fraction of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ to be $(3.63 \pm 0.43)\%$ [3]. compared with the absolute branching fraction of $\Lambda_c^+ \to X e^+ \nu_e$ measured by MARK II as $(4.5 \pm 1.7)\%$.[4]

This research [5] aims to measure the the absolute branching fraction of $\Lambda_c^+ \to Xe^+\nu_e$ more precisely, and to determine the inclusive semileptonic decay widths $\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\bar{\Gamma}(D \to Xe^+\nu_e)}$.

And the result is: $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$
$\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\bar{\Gamma}(D \to Xe^+\nu_e)} = 1.26 \pm 0.12$

$\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$: center value is larger than that of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.63 \pm 0.43)\%$. But its difference is less than 1σ. It is difficult to determine if there is other kinds of semileptonic decay. if there is, its absolute branching fraction will be much smaller than that of $\Lambda_c^+ \to Xe^+\nu_e$

$\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\bar{\Gamma}(D \to Xe^+\nu_e)} = 1.26 \pm 0.12$: This ratio is predicted to be 1.67 using an effective-quark theory calculation. [6] and 1.2 based on a calculation using the heavy-quark expansion [7]. A more precise measurement is needed to verify those theory.

This research used a double-tag method to obtain the branching fraction of the inclusive semileptonic Λ_c^+ decay.

And used a common way to choose vaild track, filter by invariant mass and beam energy, linear correction for particle identification (PID) and "Right Sign-Wrong Sign" method.

We can tell from symmetry, when electron and positron annihilations, they creates matter and antimatter. Then matter and antimatter dacays, not affected by each other. The branching fraction should be the same among them.

When it comes to Λ_c^+ and $\bar{\Lambda}_c^-$, $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ is the process that produces $\Lambda_c^\pm$.

It is difficult to figure out how many $\Lambda_c^+\bar{\Lambda}_c^-$ pairs are produces in an experiment. But due to the decay of Λ_c^+ and $\bar{\Lambda}_c^-$ are independent (statistically independent):

We always have : $\Pr(A \mid B) = \Pr(A)$, where "A" means Λ_c^+ decays into $Xe^+\nu_e$ and "B" means $\bar{\Lambda}_c^-$ decays into $\bar{p}K_S^0$ or $\bar{p}K^+\pi^-$, which have a low background and easy to reconstruct.

That is the mathematical way to explain Double-Tag in this experiment. When doing the data analysis. We first fully reconstruct one $\bar{\Lambda}_c^-$. (Effiency is about 58%)

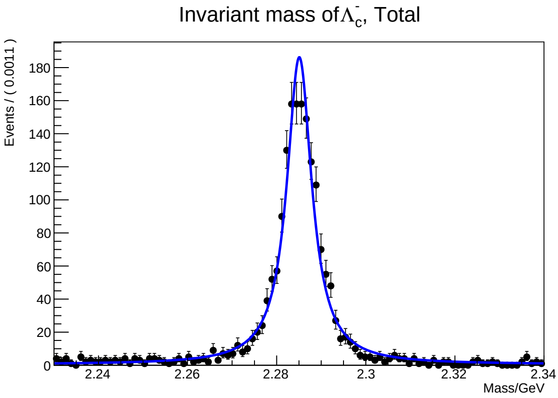

Figure: Reconstructed invariant mass from MC sample, by $\bar{p}K_S^0$ and $\bar{p}K^+\pi^-$

When reconstructed by $\bar{p}K_S^0$ and $\bar{p}K^+\pi^-$ seperately:

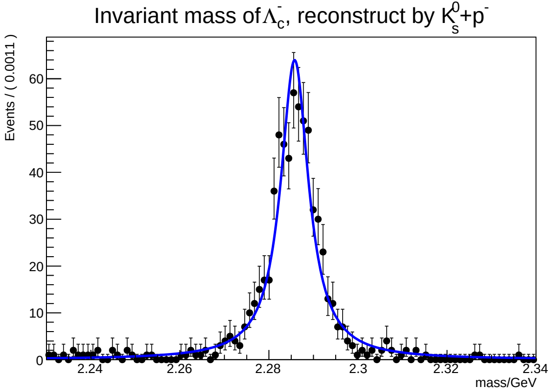

Figure: Reconstructed invariant mass from MC sample, by $\bar{p}K_S^0$

When reconstructed by $\bar{p}K_S^0$ and $\bar{p}K^+\pi^-$ seperately:

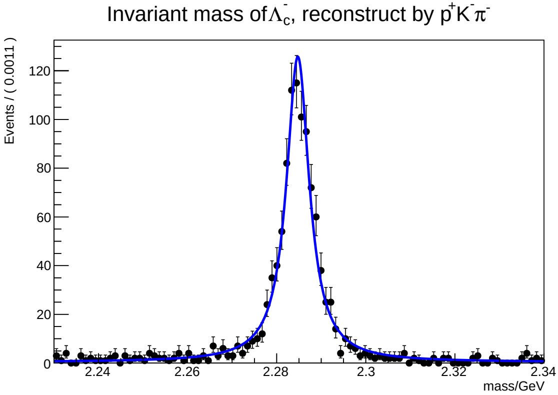

Figure: Reconstructed invariant mass from MC sample, by $\bar{p}K^+\pi^-$

To suppress combinatorial backgrounds, $\Delta E \equiv E_{\bar{\Lambda}_c^-} - E_{\mathrm{beam}}$ should in $(-3\sigma, 3\sigma)$ and $M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2/c^4 - |\vec{p}_{\bar{\Lambda}_c^-}|^2/c^2}$ should satisify $2.282 < M_{\mathrm{BC}} < 2.300\ \mathrm{GeV}/c^2$

After the selection, the effiency fails to 45%. Less than the effiency listed in the article:

Table: Summary of ΔE requirements, detection efficiencies and ST yields for the different tag modes.(Copied from article)

Tag mode	ΔE (MeV)	Efficiency (%)	Yield
$\bar{\Lambda}_c^- \to \bar{p}K_S^0$	$(-21, 19)$	56.5 ± 0.3	1214 ± 36
$\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$	$(-20, 16)$	50.1 ± 0.1	6092 ± 82

There are many restriction on PID. But even with them, there can still be mis-PID. If we regard mis-PID possibility as const, we can get:

$$\begin{pmatrix} N_e^{\text{obs}} \\ N_\pi^{\text{obs}} \\ N_K^{\text{obs}} \\ N_p^{\text{obs}} \end{pmatrix} = \begin{pmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to p} & P_{K\to p} & P_{p\to p} \end{pmatrix} \begin{pmatrix} N_e^{\text{true}} \\ N_\pi^{\text{true}} \\ N_K^{\text{true}} \\ N_p^{\text{true}} \end{pmatrix},$$

The elements in this matrix are obtained by studying control sample, for example $J/\psi \to p\bar{p}\pi^+\pi^-$ and $J/\psi \to K^+K^-K^+K^-$. Due to low $P_{\mu\to e}$, muon related PID is emitted.

Positron can be generated by other ways: γ and π^0 can decay to Dalitz decays to produce positrons. But this process always comes with positron and electron in pairs. True electron yield can be obtained by $N_{RS} - N_{WS}$

The calculation formula for final result is

$$\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = \frac{N^{\mathrm{pro}}(p_e > 200~\mathrm{MeV}/c)}{N_{\mathrm{tag}}[1 - f(p_e < 200~\mathrm{MeV}/c)]}$$

$N^{\mathrm{pro}}(p_e > 200~\mathrm{MeV}/c)$ is the corrected positron yield with momentum of more than $200~\mathrm{MeV}/c$. N_{tag} is the yield of $\bar{\Lambda}_c^-$. $f(p_e < 200~\mathrm{MeV}/c)$ is the fraction of the positron with a momentum less than $200~\mathrm{MeV}/c$.

Statistical error comes with Number of positron

Table: Positron yields in data after each procedure. The uncertainties are statistical.(copied from article)

$\Lambda_c^+ \to X e^+ \nu_e$	RS	WS
Observed yields		
tag signal region	228.0 ± 15.1	26.0 ± 5.1
tag sideband region	11.0 ± 3.3	2.0 ± 1.4
PID unfolding		
tag signal region	250.1 ± 17.1	28.3 ± 6.2
tag sideband region	12.1 ± 3.8	1.7 ± 1.5
Sideband subtraction	240.7 ± 17.4	27.0 ± 6.3
WS subtraction	213.7 ± 18.5	
Correction of tracking efficiency	272.1 ± 23.5	

Table: Sources of systematic uncertainties. And how to determine it

Source	Comments
Tag yield	signal shape, background shape and fit range
Tracking	difference between data and MC
PID	efficiency difference of $P_{e\to e}$
Sideband subtraction	change sideband region
Extrapolation	change parameters of $\Lambda e^+\nu_e$ and add unobserved channels
Data and MC statistics	vary each element in deviation
Sum	

Having done a GEANT-4 based Monte Carlo simlution, parameters related with Λ_c^+ are set to

$$\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = 0.03$$

$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.48$$

$$\mathcal{B}(\Lambda_c^+ \to pK_s^0) = 0.48$$

With 5000 events generated, 2300 reconstructed. We get to $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = 0.028$. it has a difference from input, maybe the statistical error?

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