TECHNISCHE UNIVERSITÄT DRESDEN

Partial decay widths and form factor implementation for the simulation of the Λ_c^+ decays in SHERPA

Bachelor-Arbeit
zur Erlangung des Hochschulgrades
Bachelor of Science
im Bachelor-Studiengang Physik

vorgelegt von

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2017

Eingereicht am 24. Mai 2017

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1 Introduction

One of the big questions of mankind is, why are we here. And the correspondending question is in physics is, why exists more matter than anti-matter in the universe. This thesis can't clear the question but it can be a part of the big picture.
The `LHC` (Large Hadron Collider) is one of the biggest experiments of humanity. This accelerator collides proton with protons, lead nuclei with protons or lead nuclei with lead nuclei. One detector of this big apparatus is the `LHCb`. The `LHCb` is a try to find the answer of the above question. It examines assymetries in the decay of matter and anti-matter mainly for lead-lead-collissions. And so deviations from the Standard Model. The Standard Model is a theory that describes the fundamental interactions between and the elementary particles itself very well. These deviations can result in additions to the Standard Model to consider a asymmetry between matter and anti-matter. And so lead to an answer for the matter surplus. For this the results from the experiment has to be compared to the theoratical results. But simulations are needed for the theoratical results. This comes from the different interactions that happens through a particle collision. A lot of particles are created and decay. On of the simulation tools is `Sherpa`. This program use Monte-Carlo techniques to obtain results.
One possible baryon that can be created is the Λ_c^+. It is the lightest baryon that contains a charm quark. The charm quark is like the up quark that builds together with the down quark neutrons and protons but heavier.
For a good comparison between the experimental results and the theoratical simulations is it important to implement as much particles in the simulation as possible. This leads in a better description of the reaction and so in better theoretical results.
This thesis has the goal to improve the simulation through a better implementation of the Λ_c^+ decays.

2 Basic Physical Principles

2.1 Baryons

A Baryon is a subatomic particle. It is composite and contains three quarks. The Baryons form together with the mesons the class of the hadrons. Mesons are composed of two quarks, one quark and one antiquark.
Protons and neutrons which are the components of our normal matter are baryons. These are the lightest baryons. The proton is made of two up quark and one down quark. The neutron contains two down quark and one up quark.
All observed events so far feature that the number of baryons in a reaction is observed. To use this in calculations every quark get the baryon number $B = 1/3$ and every anti-quark $B = -1/3$. In a decay from a baryon ($\sum B = 1$) the final products has to be a baryon ($\sum B = 1$) or two baryons ($\sum B = 2$) and an anti-baryon ($\sum B = -1$) and so on.

2.1.1 Λ_c^+ Baryon

The Λ_c^+ has a mass of $2286.46 \pm 0.14\text{MeV}$[3] and a mean life time of $(2.00 \pm 0.06) \cdot 10^{-13}\text{s}$[3]. It is one of the lightest charmed baryons and is made of one up, down and charm quark. His charge is $+1$ of the electron charge[3].

2.2 Decays

Decays are processes with one particale in the initial state and n particles in the final state for n= 2,3,.... The decayed particle mustn't be in the final state. This makes the difference to rediation processes. The decay process can always be transformed in the rest mass frame of the Decayer and so the summation over the energy of all particles in the final state has to be the rest energy of the decaying particle.
A decay process or more general a transision process is characterized through Fermi's golden rule(2.1).

$$\Gamma_{fi} = 2\pi |T_{fi}|^2 \rho\,(E_i) \tag{2.1}$$

In equation(2.1) T_{fi} is the transition matrix element and $\rho\left(E_i\right)$ is the density of states. The result is the transition rate Γ_{fi}.In natural units the unit of the transition rate is GeV^{-1}.
For decay process the only one intial is possible, the decayer and f is often labeled as i in literature. And so Fermi's golden rule becomes to equation (**??**).

$$\Gamma_i = 2\pi |T_i|^2 \rho\left(E\right) \tag{2.2}$$

The Γ_i is called partial decay width. And is characteristic value for a decay process. The sum over all partial decay widths is called total decay width(2.3).

$$\Gamma = \sum_i \Gamma_i \tag{2.3}$$

The total width(2.3) is an criterion for the lifetime of the decaying particle. The lifetime(**??**) of the particle in natural units is the inverse of Γ.

$$\tau = \frac{1}{\Gamma} \tag{2.4}$$

The branching ratio(2.5) is the probability to decay in a specific final state. It can be calculated with the partial and total decay width.

$$BR(i \rightarrow f) = \frac{\Gamma_f}{\Gamma} \tag{2.5}$$

The formula (2.5) use the same indices like equation(2.1).

2.3 Weak Decay

A weak decay is the transition of a particle through the weak interaction. An elementary particle that is possibly part of an composite can in this way decay to a $W^{\pm}$-Boson and an correspondending part. But the W-Boson only couple to lef-handed fundamental partciles and right-handed fundamental anti-particles. The spinor for the weak interaction than looks like (2.6). There the upper have isospin -1/2 and the lower isospin +1/2.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} d \\ u \end{pmatrix}_L, \begin{pmatrix} s \\ c \end{pmatrix}_L, \text{ etc.} \tag{2.6}$$

In (2.6) only the important particles are shown.
The value for a $W^{\pm}$ propagator is $\propto \frac{1}{q^2 - m_W^2}$. But in most process the transfered momentum is much lower compared to the Mass of the $W^{\pm}$ boson because it is the mass difference of the initial particle and the final particle that are connected through the $W^{\pm}$ vertex. This leads to an estimation there the propagator becomes to $\propto \frac{1}{m_W^2} \propto G_F$. G_F is the Fermi constant for

the weak interaction and the process looks like a one to three vertex because $W^{\pm}$ boson is not stable and decays in other particles.
The measurement of leptons are mostly very accurate in a detector and the calculation of the transisition matrix element becomes easier for leptonic decays only this decays are considered. For the Λ_c^+ exists the following Feynman diagram(2.1). The Λ_c^+ can decay in a neutron or a Lambda as baryon and a positron or anit-muon as lepton plus the correspondending neutrino to observe the lepton number.

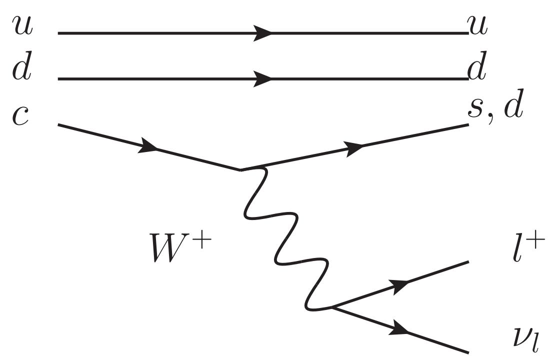

Figure 2.1: Semileptonic decay modes of the Λ_c^+ into a neutron (udd) or a Λ (uds), an positron or an anti-muon and the correspondending neutrino (own graphic)

2.4 V-A current

The value of a Vertex where two pertinent leptons transforms into a $W^{\pm}$ boson is $-i\frac{g}{2\sqrt{2}}\gamma^{\mu}\left(1-\gamma^5\right)$. If the sum is splitted, the the term without γ^5 is called vector and the part with the γ^5 axial-vector through the geometrical effect of the γ-matrix. The transition from quarks needs an additional factor V_{if}. i is the quark and in the initial state and f the quark in the final state. The factor comes from the CKM-matrix[2]. The matrix from [2] is shown in (2.7).

$$V_{CKM} = \begin{bmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{bmatrix} \tag{2.7}$$

With the general Feynman rules for vertices and propagators the transition matrix element becomes to (2.8) like in [10, Eq. 1].

$$T = \frac{G_F}{\sqrt{2}} V_{Qq} \bar{u}_l \gamma^{\mu} \left(1-\gamma^5\right) u_{\nu_l} \langle B(p', s') | J_{\mu} | \Lambda_c(p, s) \rangle \tag{2.8}$$

The B in (2.8) stands for the neutron or Λ. The current J_μ can be splitted in a vector-axial and an axial part $J_\mu = V_\mu - A_\mu$ like in (2.9).

$$\begin{aligned}\langle B(p',s')|V_\mu|\Lambda_c(p,s)\rangle &= \bar{u}(p',s')\left(F_1(q^2)\gamma_\mu + F_2(q^2)\frac{p_\mu}{m_{\Lambda_c}} + F_3(q^2)\frac{p'_\mu}{m_B}\right)u(p,s)\\ \langle B(p',s')|A_\mu|\Lambda_c(p,s)\rangle &= \bar{u}(p',s')\left(G_1(q^2)\gamma_\mu + G_2(q^2)\frac{p_\mu}{m_{\Lambda_c}} + G_3(q^2)\frac{p'_\mu}{m_B}\right)\gamma^5 u(p,s)\end{aligned} \tag{2.9}$$

The F_i and G_i are form factors for the transition. They are specific for the initial and final baryons and describe the different behavior of the quarks in a bound state in contrast to the free decay. The functional behavior of these form factors is related to $q^2 = (p - p')^2$.

2.5 Monte-Carlo basics

The `Sherpa` software use Monte-Carlo methods to calcullate the dynamics of the process for the phase space integration of the partial width. To understand this method Fermi's golden rule(2.1) has to be written as an integral. This integral can be ontained from the density of states. A formula like [11, Eq. 2.38] is the result of this equation. The differential dacay rate is an important part because with Monte-Carlo the integral can be performed. For this a point in the phase space is diced. The differential decay rate $d\Gamma$ is calculated. If the Ratio between the differential decay rate and the maximum decay rate is bigger as a random number between zero and one the event is accepted. This points will be collected and form the integral and so the decay rate at the end.

3 Methods and Implementation

3.1 Decaysdata.db

`Sherpa` use for the decays from all kinds of particles the decay channels and branching ratios from the `Decaysdata.db`. This database has to be updated manually with data from the Particle Data Group (PDG) because there exists no automation for this work. Also data from other sources are included, e.g. EvtGen.
Good results need actual data. The first part is to update the branching ratios and deyays. For the $\Xi(1690)$ was an implementation not possible because there exists to few events about futher decays. The conclusion of different events needs a lot of attention. For some events like $\Lambda_c^+ \to \Sigma(1385)^- + \pi^+ + \pi+$ only the channel $\Sigma(1385) \to \Lambda + \pi$ was recognized. So a division with the BR($\Sigma(1385) \to \Lambda + \pi$) was needed because `Sherpa` handle further decays and consider all different decays of the $\Sigma(1385)^-$. Table (A.1) was revealed with this knowledge. An abstract is visible in (3.1).

Table 3.1: Extract of the changes in the Decays.dat from the Λ_c^+

Status	Outgoing Part.	BR(Delta BR)[Origin]	Decay
Modes with nucleons/Deltas			
old	2212,-311	0.023(0.006)[PDG]	$\Lambda_c^+ \to P^+ + K_b$
new	2212,310	0.0158(0.0008)[PDG]	$\Lambda_c^+ \to P^+ + K_s$
old	2212,-321,211	0.028(0.008)[PDG]	$\Lambda_c^+ \to P^+ + K^- + \pi^+$
new	2212,-321,211	0.035(0.004)[PDG]	
old	2212,-311,111	0.033(0.010)[PDG]	$\Lambda_c^+ \to P^+ + K_b + \pi$
new	2212,310,111	0.0199(0.0013)[PDG]	
old	2212,-311,221	0.012(0.004)[PDG]	$\Lambda_c^+ \to P^+ K_b + \eta$
old	2212,211,211,-211,-211	0.018(0.012)[PDG]	$\Lambda_c^+ \to P^+ + \pi^+ + \pi^+ + \pi^- + \pi^-$
new	2212,211,211,-211,-211	0.0023(0.0015)[PDG]	
S = 0			
old	2212,9010221	0.0028(0.0019)[PDG]	$\Lambda_c^+ \to P^+ + f(0980)$
new	2212,9010221	0.0035(0.0023)[PDG]	
S = 0			
deleted	2212,211,-211	0.0007(0.0007)[PDG]	$\Lambda_c^+ \to P^+ + \pi^+ + \pi^-$

S = 0			
old	2224,-321	0.0086(0.003[PDG]	$\Lambda_c^+ \to \Delta(1232)^{++} + K^-$
new	2224,-321	0.0109(0.0025)[PDG]	
Modes with hyperons			
old	3122,211	0.0107(0.0028)[PDG]	$\Lambda_c^+ \to \Lambda + \pi^+$
new	3122,211	0.0130(0.0007)[PDG]	
created	3122,211,111	0.071(0.0004)[PDG]	$\Lambda_c^+ \to \Lambda + \pi^+ + \pi$
created	3122,213	0.036(0.013)[PDG]	$\Lambda_c^+ \to \Lambda + \rho(770)^+$
S = 0			
old	3122,321	0.0005(0.00016)[PDG]	$\Lambda_c^+ \to \Lambda + K^+$
new	3122,321	0.00061(0.00012)[PDG]	
created	3112,211,211	0.021(0.004)[PDG]	$\Lambda_c^+ \to \Sigma^- + \pi^+ + \pi^+$
semileptonic modes			
old	3122,12,-11	0.021(0.006)[PDG]	$\Lambda_c^+ \to \Lambda + \nu_e + e^+$
new	3122,12,-11	0.036(0.004)[PDG]	
old	3122,14,-13	0.020(0.007)[PDG]	$\Lambda_c^+ \to \Lambda + \nu_\mu + \mu^+$
new	3122,14,-13	0.036(0.004)[PDG]	

In the case of $\Lambda_c^+ \to P^+\pi^+ + \pi^-$ was the decay already included in $\Lambda_c^+ \to P^+ + f(0980)$. K_b was removed from the PDG and only K_s exists. For $\Lambda_c^+ \to \Lambda + \eta + \pi^+$ give the difference between $\Lambda + \pi^- + \pi + \pi^+ + \pi^+$ and $\Sigma(1385)^+ + \eta$ the right value because an η decays in $\pi^+ + \pi^-$ and a $\Sigma(1385)$ to $\Lambda + \pi$. But the decay of the $\Sigma(1385)$ is a separate channel.
These decays are selected because the full list would be too long and so it is visible that some channel becomes likelier. But as an compensation other process has to become less probable. These process are in most cases very similiar and redistribution rests upon a better identification of the final decay states and a better particle reconstruction. One of the important changes is the increase of the branching ratios from the semileptonic decays by nearly 1%. Other important process that didn't changed are shown in table(3.2)

Table 3.2: Decays in a neutron in the Decays.dat from the Λ_c^+

Status	Outgoing Part.	BR(Delta BR)[Origin]	Decay
semileptonic modes			
old	2112,12,-11	0.003[EvtGen]	$\Lambda_c^+ \to n + \nu_e + e^+$
old	2112,14,-13	0.003[EvtGen]	$\Lambda_c^+ \to n + \nu_\mu + \mu^+$

The branching for these semileptonic decays only simulated. The reason is that most of the modern detectors can't detect neutrons very well. This comes from the neutral electric charge

and the long lifetime of the neutron. An improved measurement would be recommended because this processes are important for the form factor calculation. The neutron is often considered as the final decay state oif the Λ_c^+.
All these changes leads to a sum of all branching ratios from $87,98\%$. This is a pretty good value and very close to 100%. This means that the decay is very good abstracted.

3.2 Form Factor conversion

The two formulas in (2.9) show one popular parametrization for the V-A-Current another possible and popular writing is given in (3.1).

$$\begin{aligned}\langle B(p',s')|V_\mu|\Lambda_c(p,s)\rangle &= \bar{u}(p',s')\left(f_1^V(q^2)\gamma_\mu + f_2^V(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{m_{\Lambda_c}} + f_3^V(q^2)\frac{q_\mu}{m_{\Lambda_c}}\right)u(p,s)\\ \langle B(p',s')|A_\mu|\Lambda_c(p,s)\rangle &= \bar{u}(p',s')\left(f_1^A(q^2)\gamma_\mu + f_2^A(q^2)ß\sigma_{\mu\nu}fracq^\nu m_{\Lambda_c} + f_3^A(q^2)\frac{q_\mu}{m_{\Lambda_c}}\right)\gamma^5 u(p,s)\end{aligned} \tag{3.1}$$

In this notation is $q = p - p'$. A convsersion formula is now needed for the different parametrization of the current. The equations in [4, Eq. 15] give one direction for transformation. But most of the following form factors are in the form with p and p' and not with q. So the inversion of the given transformation would be the easiest way to get a decent formula. Another fact is that the current for an baryon baryon transition in `Sherpa` is already in the form like (2.9). The use of this parametrization let the implementation become a lot easier. The first step is to create a transformation matrix like in (3.2)

$$\begin{pmatrix} f_1^V \\ f_2^V \\ f_3^V \\ f_1^A \\ f_2^A \\ f_3^A \end{pmatrix} = \begin{bmatrix} 1 & \frac{m_{\Lambda_c}+m_B}{2m_{\Lambda_c}} & \frac{m_{\Lambda_c}+m_B}{2m_B} & 0 & 0 & 0 \\ 0 & -\frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} & 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -\frac{m_{\Lambda_c}-m_B}{2m_{\Lambda_c}} & -\frac{m_{\Lambda_c}-m_B}{2m_B} \\ 0 & 0 & 0 & 0 & -\frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} \\ 0 & 0 & 0 & 0 & \frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} \end{bmatrix} \cdot \begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ G_1 \\ G_2 \\ G_3 \end{pmatrix} \tag{3.2}$$

The block structure of the matrix is a mathemtaical manifestation of the independence of the vector and axial-vector part. This matrix can be splitted in two equations(3.3).

$$\begin{pmatrix} f_1^V \\ f_2^V \\ f_3^V \end{pmatrix} = \begin{bmatrix} 1 & \frac{m_{\Lambda_c}+m_B}{2m_{\Lambda_c}} & \frac{m_{\Lambda_c}+m_B}{2m_B} \\ 0 & -\frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} \\ 0 & \frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} \end{bmatrix} \cdot \begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix}$$
$$\begin{pmatrix} f_1^A \\ f_2^A \\ f_3^A \end{pmatrix} = \begin{bmatrix} 1 & -\frac{m_{\Lambda_c}-m_B}{2m_{\Lambda_c}} & -\frac{m_{\Lambda_c}-m_B}{2m_B} \\ 0 & -\frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} \\ 0 & \frac{1}{2} & -\frac{m_{\Lambda_c}}{2m_B} \end{bmatrix} \cdot \begin{pmatrix} G_1 \\ G_2 \\ G_3 \end{pmatrix} \tag{3.3}$$

The matrices can be inverted if the determinant is unequal to zero. The determinant of both matrices are the same(3.4). This comes from the block structure with the zeroes in the first column.

$$det(\dots) = \frac{m_{\Lambda_c}}{2m_B} \tag{3.4}$$

If the mass of the Λ_c^+ is nonzero than the matrices are invertible. And obviously is this true. The matrix for G_i is really in the fashion of the one for F_i. So the inverting has only be done ones. The matrices in (3.5) are calculated.

$$\begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix} = \begin{bmatrix} 1 & \frac{3m_{\Lambda_c}+m_B}{4m_{\Lambda_c}} & -\frac{m_{\Lambda_c}+m_B}{4m_B} \\ 0 & -1 & 1 \\ 0 & -\frac{m_B}{2m_{\Lambda_c}} & -\frac{m_B}{2m_{\Lambda_c}} \end{bmatrix} \cdot \begin{pmatrix} f_1^V \\ f_2^V \\ f_3^V \end{pmatrix}$$
$$\begin{pmatrix} G_1 \\ G_2 \\ G_3 \end{pmatrix} = \begin{bmatrix} 1 & -\frac{3m_{\Lambda_c}-m_B}{4m_{\Lambda_c}} & \frac{m_{\Lambda_c}+m_B}{4m_B} \\ 0 & -1 & 1 \\ 0 & -\frac{m_B}{2m_{\Lambda_c}} & -\frac{m_B}{2m_{\Lambda_c}} \end{bmatrix} \cdot \begin{pmatrix} f_1^A \\ f_2^A \\ f_3^A \end{pmatrix} \tag{3.5}$$

And finally for every form factor a transformation formula(3.6) can be obtained.

$$\begin{aligned}
F_1 &= f_1^V + \frac{m_{\Lambda_c}+m_B}{4}\left(\frac{3f_2^V}{m_{\Lambda_c}} - \frac{f_3^V}{m_B}\right) \\
F_2 &= -f_2^V + f_3^A \\
F_3 &= -\frac{m_B}{2m_{\Lambda_c}}\left(f_2^V + f_3^V\right) \\
G_1 &= f_1^A + \frac{m_{\Lambda_c}-m_B}{4}\left(-\frac{3f_2^V}{m_{\Lambda_c}} + \frac{f_3^V}{m_B}\right) \\
G_2 &= -f_2^A + f_3^A \\
G_3 &= -\frac{m_B}{2m_{\Lambda_c}}\left(f_2^A + f_3^V\right)
\end{aligned} \tag{3.6}$$

The basic class FormFactor_Base from VA_B_B_FFs in `HADRONS++/Current_Library/VA_B_B.H` is now extend with additional inline functions for the transformation. To use every time the same parametrization and didn't mix them.

3.3 Prevoius Form Factor implementation

At first it is important to know wich current parametrization is already used by the `VA_B_B.C` in `Sherpa`. With this information the right form can be choosen. For a natural transition between two baryons the different coefficient (3.7) are computed. A natural transition means that the decayer and the daughter baryon have the same parity.

$$\begin{aligned} c_{R1} &= V_1 - A_1 \\ c_{L1} &= -V_1 - A_1 \\ c_{R2} &= V_2 - A_2 \\ c_{L2} &= -V_2 - A_2 \\ c_{R3} &= V_3 - A_3 \\ c_{L3} &= -V_3 - A_3 \end{aligned} \tag{3.7}$$

V_i and A_i comes from the choosen from factor model. The following current(3.8) is sumed ove all possible helicities from the decaying h_0 and the daughter baryon h_1.

$$\begin{aligned} V_\mu = L_\mu(1, h_1, 0, h_0, c_{R1}, c_{L1}) + \\ \frac{p_{0,\mu}}{m_0} * Y(1, h_1, 0, h_0, c_{R2}, c_{L2}) + \\ \frac{p_{1,\mu}}{m_1} * Y(1, h_1, 0, h_0, c_{R3}, c_{L3}) \end{aligned} \tag{3.8}$$

The definition of L_μ is given in [11, Eq. A.96] and the Y in [11, Eq. A.94]. They are visible again in (**??**).

$$\begin{aligned} L_\mu(1, h_1, 0, h_0, c_{R1}, c_{L1}) &= \bar{u}(p_1, h_1)\gamma_\mu \left(c_{R1}P_R + c_{L1}P_L\right) u(p_0, h_0) \\ Y(1, h_1, 0, h_0, c_{R2}, c_{L2}) &= \bar{u}(p_1, h_1) \left(c_{R2}P_R + c_{L2}P_L\right) u(p_0, h_0) \\ Y(1, h_1, 0, h_0, c_{R3}, c_{L3}) &= \bar{u}(p_1, h_1) \left(c_{R3}P_R + c_{L3}P_L\right) u(p_0, h_0) \end{aligned} \tag{3.9}$$

The projection operators that are used in (**??**) are defined in (3.10)

$$\begin{aligned} P_R &= \frac{1}{2}\left(1 + \gamma_5\right) \\ P_L &= \frac{1}{2}\left(1 - \gamma_5\right) \end{aligned} \tag{3.10}$$

This all equations together form a current wich is similiar to {(2.9). This can also easily been seen through the signs of the γ_5 and the signs of the c_R and c_L. All other current parametrization have to be converted to observe the existing behavior.

3.4 Observables

Two observables are adapted from simulations of the BELLE experiment to compare the different form factors. The first is q^2 which is defined in (3.11).

$$q^2 = (p_{\Lambda_c} - p_B)^2 \tag{3.11}$$

And the second is the recoil of the W in (3.12)

$$w = \frac{p_{\Lambda_c}^2 + p_B^2 - (p_{\Lambda_c} - p_B)^2}{2 \cdot \sqrt{p_{\Lambda_c}^2} \cdot \sqrt{p_B^2}} \tag{3.12}$$

3.5 Form Factor Models

3.5.1 Covariant Confined Quark Model (CCQM)

The idea behind the covariant confined quark model is to use two loops Feynman diagrams with free quark propagators. The high energy behavior of the loop integrations is soften. This model was developed for mesons but is extended to baryons. It is also possible to successfully calculate tetraquark states with this theory.
For the transition to $\Lambda + l^+ + \nu_l$ the paper[7] was considered and for $n + l^+ + \nu_l$ the paper[6]. The parametrization of the form factor is given by (3.13)

$$f(q^2) = \frac{F(0)}{1 - as + bs^2} \text{ with } s = \frac{q^2}{m_{\Lambda_c}} \tag{3.13}$$

The parameters F(0), a and b are taken from the numerical results of [7].

3.5.2 Non relativistic Quark Model (NRQM)

Baryons with a heavy quark possesses a special symmetry. This symmetry is called heavy quark symmetry. This is based on works from Isgur and Wise. The name of the theory behind that is heavy quark effective theory (HQET). The main impact to the characteristics of the baryon results from the degrees of freedom of the light quarks and are independent from the degrees of freedom of the heavy quark.
This form factor can be used to calculate transistions to excited Λ baryons [9]. The parametriza-

tion of the form factors (3.14) a more complicated compared to the other ones.

$$
\begin{aligned}
F &= \left(a_0 + a_2 q^2 + a_4 q_4\right) e^{-\frac{3 m_\sigma^2 p_\Lambda^2}{2 m_\Lambda^2 \alpha_{\lambda\lambda'}^2}} \\
p_\Lambda &= \frac{1}{2 m_\Lambda} \lambda^{\frac{1}{2}}(m_{\Lambda_c}^2, m_\Lambda^2, q^2) \\
\lambda(x,y,z) &= x^2 + y^2 + z^2 - 2xy - 2yz - 2zx (\text{triangle function}) \\
\alpha_{\lambda\lambda'} &= \sqrt{\frac{\alpha_\lambda^2 + \alpha_{\lambda'}^2}{2}}
\end{aligned}
\tag{3.14}
$$

In equation(3.14) is m_σ the mass of the light quark obtained from [9, p. 13/I] and the α_λ are size parameters of the baryons from [9, p. 13/II].

3.5.3 Light-Cone Sume Rule (LCSR)

The light-cone sume rule is a vary famous technique in the class of QCD sum rules. The basic idea is that the vacuum condensates carry no momentum. The light-cone expansion is used with increasing twist. With this model was the transition into $\Lambda + l^+ + \nu_l$ in [8] computed.
The parametrization(3.15) is through the same values for the first two axial-vector and vector form factors very simple

$$
\begin{aligned}
f_1^V &= f_1^A \\
f_2^V &= f_2^A \\
f_i(q^2) &= \frac{f_i(0)}{a_2 s^2 + a_1 s + 1} \text{ with } s = \frac{q^2}{m_{\Lambda_c}}
\end{aligned}
\tag{3.15}
$$

$f_i(0)$, a_2 and a_1 are parameters of this parametrization. Only the first two factors are nonzero.

3.5.4 Relativistic Quark Model (RQM)

The relativistic quark model[5] is based on the diquark wave function and the baryon wave function of the bound quark-diquark state. The calculation were done with relativistic quasipotential equation of the Schrödinger type. All computation were relativistically done.
It can predict senmileptonic transitions into n as well as into Λ. The parametrization(3.16) was done until a very high order of the q^2.

$$
F(q^2) = \frac{F(0)}{1 - \sigma_1 s + \sigma_2 s^2 + \sigma 31 s^3 + \sigma_4 s^4} \text{ with } s = \frac{q^2}{m_{\Lambda_c}} \tag{3.16}
$$

3.5.5 QCD Sum Rule (QCDSR)

In the article [1] are nonperturbative aspects used. The approach of the QCD sum-rule is the expansion in local operators. Here is also the HQET usd to reduce the complexity. $\Lambda + l^+ + \nu_l$

is considered in the article.
In this Model two different parametrizations exists. The pole parametrization (3.17) is used like in the other models. But this pole parametrization is a lot simpler through relations between the form factors.

$$\begin{aligned} f_1^A &= -f_1^V \\ f_2^A &= f_2^V \\ f_i^V(q^2) &= \frac{a_0}{a_1 - q^2} \end{aligned} \tag{3.17}$$

The other form of the parametrization (3.18) is more complicated but through the exponential ansatz interesting.

$$\begin{aligned} f_1^A &= -f_1^V \\ f_2^A &= -f_2^V \\ f_1^V(q^2) &= e^{\frac{q^2 - a_1}{a_0}} \\ f_2^V(q^2) &= \frac{a_0}{a_1 - q^2} \end{aligned} \tag{3.18}$$

The third form factor is in both cases zero

4 Evaluation and Discussion

5 Summary and Outlook

6 Bibliography

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A Appendix

A.1 Devays.dat

Table A.1: Full list of changes in the Decays.dat from the Λ_c^+

Status	Outgoing Part.	BR(Delta BR)[Origin]	Decay
Modes with nucleons/Deltas			
old	2212,-311	0.023(0.006)[PDG]	$\Lambda_c^+ \to P^+ + K_b$
new	2212,310	0.0158(0.0008)[PDG]	$\Lambda_c^+ \to P^+ + K_s$
old	2212,-313	0.016(0.005)[PDG]	$\Lambda_c^+ \to P^+ + K^*(892)_b$
new	2212,-313	0.0198(0.0028)[PDG]	
old	2212,-321,211	0.028(0.008)[PDG]	$\Lambda_c^+ \to P^+ + K^- + \pi^+$
new	2212,-321,211	0.035(0.004)[PDG]	
old	2212,-311,111	0.033(0.010)[PDG]	$\Lambda_c^+ \to P^+ + K_b + \pi$
new	2212,310,111	0.0199(0.0013)[PDG]	
old	2212,-311,221	0.012(0.004)[PDG]	$\Lambda_c^+ \to P^+ K_b + \eta$
new	2212,-311,221	0.016(0.004)[PDG]	
old	2212,-311,211,-211	0.026(0.007)[PDG]	$\Lambda_c^+ \to P^+ + K_b + \pi^+ \pi^-$
new	2212,-311,211,-211	0.049(0.004)[PDG]	
old	2212,-311,211,-211	0.026(0.007)[PDG]	$\Lambda_c^+ \to P^+ + K_b + \pi^+ + \pi^-$
new	2212,310,211,-211	0.0166(0.0012)[PDG]	
old	2212,-323,211	0.016(0.005)[PDG]	$\Lambda_c^+ \to P^+ + K^*(892)_b^+ + \pi^+$
new	2212,-323,211	0.015(0.005)[PDG]	
old	2212,-321,211,111	0.036(0.012)[PDG]	$\Lambda_c^+ \to P^+ + K^- + \pi^+ + \pi$
new	2212,-321,211,111	0.046(0.09)[PDG]	
old	2212,-321,211,211,-211	0.0011(0.0008)[PDG]	$\Lambda_c^+ \to P^+ + K^- + \pi^+ + \pi^+ + \pi^-$
new	2212,-321,211,211,-211	0.0014(0.001)[PDG]	
old	2212,-321,211,111,111	0.008(0.004)[PDG]	$\Lambda_c^+ \to P^+ + K^- + \pi^+ + \pi + \pi$
new	2212,-321,211,111,111	0.01(0.005)[PDG]	
old	2212,333	0.00082(0.00027)[PDG]	$\Lambda_c^+ \to P^+ + \phi(1020)$
new	2212,333	0.00104(0.00021)[PDG]	

S = 0			
old	2212,321,-321	0.00035(0.00017)[PDG]	$\Lambda_c^+ \to P^+ + K^+ + K^-$
new	2212,321,-321	0.00044(0.00018)[PDG]	
S = 0			
old	2212,211,211,-211,-211	0.018(0.012)[PDG]	$\Lambda_c^+ \to P^+ + \pi^+ + \pi^+ + \pi^- + \pi^-$
new	2212,211,211,-211,-211	0.0023(0.0015)[PDG]	
S = 0			
old	2212,9010221	0.0028(0.0019)[PDG]	$\Lambda_c^+ \to P^+ + f(0980)$
new	2212,9010221	0.0035(0.0023)[PDG]	
S = 0			
deleted	2212,211,-211	0.0007(0.0007)[PDG]	$\Lambda_c^+ \to P^+ + \pi^+ + \pi^-$
S = 0			
old	2224,-321	0.0086(0.003[PDG]	$\Lambda_c^+ \to \Delta(1232)^{++} + K^-$
new	2224,-321	0.0109(0.0025)[PDG]	
Modes with hyperons			
old	3122,211	0.0107(0.0028)[PDG]	$\Lambda_c^+ \to \Lambda + \pi^+$
new	3122,211	0.0130(0.0007)[PDG]	
created	3122,211,111	0.071(0.0004)[PDG]	$\Lambda_c^+ \to \Lambda + \pi^+ + \pi$
created	3122,213	0.036(0.013)[PDG]	$\Lambda_c^+ \to \Lambda + \rho(770)^+$
S = 0			
old	3122,321	0.0005(0.00016)[PDG]	$\Lambda_c^+ \to \Lambda + K^+$
new	3122,321	0.00061(0.00012)[PDG]	
old	3122,211,113	0.011(0.005)[PDG]	$\Lambda_c^+ \to \Lambda + \pi^+ + \rho(770)$
new	3122,211,113	0.015(0.006)[PDG]	
old	3122,221,211	0.018(0.006)[PDG]	$\Lambda_c^+ \to \Lambda + \eta + \pi^+$
new	3122,221,211	0.022(0.005)[PDG]	
old	3122,223,211	0.018(0.006)[PDG]	$\Lambda_c^+ \to \Lambda + \omega(782) + \pi^+$
new	3122,223,211	0.015(0.005)[PDG]	
old	3122,321,-311	0.0047(0.0015)[PDG]	$\Lambda_c^+ \to \Lambda + K^+ + K_b$
new	3122,321,-311	0.0057(0.0011)[PDG]	
old	3114,211,211	0.0055(0.0017)[PDG]	$\Lambda_c^+ \to \Sigma(1385)^- + \pi^+ + \pi^+$
new	3114,211,211	0.0090(0.0018)[PDG]	
created	3112,211,211	0.021(0.004)[PDG]	$\Lambda_c^+ \to \Sigma^- + \pi^+ + \pi^+$
old	3212,211	0.0105(0.0028)[PDG]	$\Lambda_c^+ \to \Sigma + \pi^+$
new	3212,211	0.0129(0.0007)[PDG]	
S = 0			

old	3212,321	0.00042(0.00013)[PDG]	$\Lambda_c^+ \to \Sigma + K^+$
new	3212,321	0.00052(0.00008)[PDG]	
old	3212,211,211,-211	0.0083(0.0031)[PDG]	$\Lambda_c^+ \to \Sigma + \pi^+ + \pi^+ + \pi^-$
new	3212,211,211,-211	0.0113(0.0029)[PDG]	
old	3222,111	0.0100(0.0034)[PDG]	$\Lambda_c^+ \to \Sigma^+ + \pi$
new	3222,111	0.0124(0.001)[PDG]	
old	3222,221	0.0055(0.0023)[PDG]	$\Lambda_c^+ \to \Sigma^+ + \eta$
new	3222,221	0.0070(0.0023)[PDG]	
old	3222,211,-211	0.013(0.005)[PDG]	$\Lambda_c^+ \to \Sigma^+ + \pi^+ + \pi^-$
new	3222,211,-211	0.0457(0.0029)[PDG]	
S = 0			
old	3222,313	0.002[EvtGen]	$\Lambda_c^+ \to \Sigma^+ + K^*(892)$
new	3222,313	0.0036(0.001)[PDG]	
old	3222,223	0.027(0.01)[PDG]	$\Lambda_c^+ \to \Sigma^+ + \omega(782)$
new	3222,223	0.0174(0.0021)[PDG]	
old	3222,333	0.0031(0.0009)[PDG]	$\Lambda_c^+ \to \Sigma^+ + \phi(1020)$
new	3222,333	0.0040(0.0006)[PDG]	
old	3224,113	0.0037(0.0031)[PDG]	$\Lambda_c^+ \to \Sigma(1385)^+ + \rho(770)$
new	3224,113	0.0072(0.0046)[PDG]	
old	3224,221	0.0085(0.0033)[PDG]	$\Lambda_c^+ \to \Sigma(1385i)^+ + \eta$
new	3224,221	0.00124(0.00037)[PDG]	
old	3224,211,-211	0.007(0.004)[PDG]	$\Lambda_c^+ \to \Sigma(1385)^+ + \pi^+ + \pi^-$
new	3224,211,-211	0.011(0.006)[PDG]	
old	3322,321	0.0039(0.0014)[PDG]	$\Lambda_c^+ \to \Xi + K^+$
new	3322,321	0.0050(0.0012)[PDG]	
old	3312,321,211	0.0025(0.001)[PDG]	$\Lambda_c^+ \to \Xi^- + K^+ + \pi^+$
new	3312,321,211	0.0062(0.0006)[PDG]	
old	3324,321	0.0026(0.001)[PDG]	$\Lambda_c^+ \to \Xi(1530) + K^+$
new	3324,321	0.0033(0.0009)[PDG]	
semileptonic modes			
old	3122,12,-11	0.021(0.006)[PDG]	$\Lambda_c^+ \to \Lambda + \nu_e + e^+$
new	3122,12,-11	0.036(0.004)[PDG]	
old	3122,14,-13	0.020(0.007)[PDG]	$\Lambda_c^+ \to \Lambda + \nu_\mu + \mu^+$
new	3122,14,-13	0.036(0.004)[PDG]	

Erklärung

Hiermit erkläre ich, dass ich diese Arbeit im Rahmen der Betreuung am Institut für Kern- und Teilchenphysik ohne unzulässige Hilfe Dritter verfasst und alle Quellen als solche gekennzeichnet habe.

Sven Schiffner
Dresden, Mai 2017