

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

Sven Schiffner
geboren am 28.10.1994 in Sebnitz

Institut für Kern- und Teilchenphysik
Fachrichtung Physik
Fakultät Mathematik und Naturwissenschaften
Technische Universität Dresden
2017

Eingereicht am 24. Mai 2017

1. Gutachter: Dr. Frank Siegert
2. Gutachter: Prof. Dr. Michael Kobel

Summary

Abstract

English:

Abstract

Deutsch

Contents

1	Introduction	7
2	Basic Physical Principles	9
2.1	Baryons	9
2.1.1	Λ_c^+ Baryon	9
2.2	Decays	9
2.3	Weak Decay	10
2.4	V-A current	11
2.5	Monte-Carlo methods	12
3	Methods and Implementation	13
3.1	Decays Data	13
3.2	Form Factor conversion	15
3.3	Previous Form Factor implementation	16
3.4	Observables	18
3.5	Form Factor Models	18
3.5.1	Covariant Confined Quark Model (CCQM)	18
3.5.2	Non relativistic Quark Model (NRQM)	18
3.5.3	Light-Cone Sume Rule (LCSR)	19
3.5.4	Relativistic Quark Model (RQM)	19
3.5.5	QCD Sum Rule (QCDSR)	19
4	Evaluation and Discussion	21
4.1	Decay table	21
4.2	Form Factor Models	28
4.2.1	$\Lambda_c^+ \rightarrow \Lambda + l^+ + \nu_l$	28
4.2.2	$\Lambda_c^+ \rightarrow n + l^+ + \nu_l$	32
5	Summary and Outlook	35
6	Bibliography	37
A	Appendix	39

A.1	Decays.dat	39
A.2	Primary Decays	42
A.3	Complete Decays	47

1 Introduction

One of the big questions of mankind is, why are we here. And the corresponding question in physics is, why more matter than anti-matter exists in the universe. This thesis cannot 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 asymmetries in the decay of matter and anti-matter mainly for proton-proton-collisions. 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 have to be compared to the theoretical results. But simulations are needed for the theoretical results. This comes from the different interactions that happens through a particle collision. A lot of particles are created and decay. One of the simulation tools is **Sherpa**[6]. 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 neutrons and protons together with the down quark, but heavier.

For a good comparison between the experimental results and the theoretical simulations it is important to implement baryons and not only bare quarks in the simulation. The behavior of quarks in bound states is different to free quarks that didn't exists in nature. So the hadronization and the decay of the hadrons are important processes. This processes have to be recognized to get good theoretical predictions..

This thesis has the goal to improve the simulation through a better implementation of the Λ_c^+ decays.

I want to thanks Johannes Krause, Daniel Reichelt and Sebastian Liebschner for their help.

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 quarks and one down quark. The neutron contains two down quarks 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. Its 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 $n=2,3,\dots$. The decayed particle must not be in the final state. This makes the difference to radiation processes. The decay process can always be transformed in to 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:

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

where T_{fi} is the transition matrix element and $\rho(E_i)$ 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} .

The Γ_{fi} is also called partial decay width. And is characteristic value for a decay process. The sum over all partial decay widths is called total decay width:

$$\Gamma_i = \sum_f \Gamma_{fi}. \quad (2.2)$$

The total width(2.2) is an criterion for the lifetime of the decaying particle. The lifetime of the particle in natural units is the inverse of Γ_i :

$$\tau_i = \frac{1}{\Gamma_i}. \quad (2.3)$$

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

$$BR(i \rightarrow f) = \frac{\Gamma_f}{\Gamma}. \quad (2.4)$$

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 a correspondending particle. But the W-Boson only couple to lef-handed fundamental particles and right-handed fundamental anti-particles. The spinor for the weak interaction than looks like (2.5). There the upper particle have isospin -1/2 and the lower isospin +1/2.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} s \\ c \end{pmatrix}_L, \begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}_R, \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}_R \text{ etc.} \quad (2.5)$$

In (2.5) only the particles are shown that are relevant for this thesis.

In the Feynman diagram 2.1 the semileptonic decay of a Λ_c^+ is visible. The up and down quark from the Λ_c^+ are unchanged. They can only influence the transition matrix element through a different behavior of the charm quark. The charm quark transforms through the weak decay in to a down or strange quark. The down quark forms with the other two quarks a neutron and the strange quark a Λ . The emitted W^+ -Boson decays leptonic in an anti-lepton and the correspondending neutrino. Other decays of the W^+ -boson are possible. For this thesis only the semileptonic decays channels are relevant. The complete dynamic of the process will be discussed in 2.4. In this section we will take a closer look at the W^\pm propagator.

The value for a W^\pm propagator is $\frac{g_w^2}{8} \frac{1}{q^2 - m_W^2}$. The transferred momentum is $q^2 = (p_f - p_i)^2$. It is limited by the initial state mass and for most decays this is much less than the mass of the

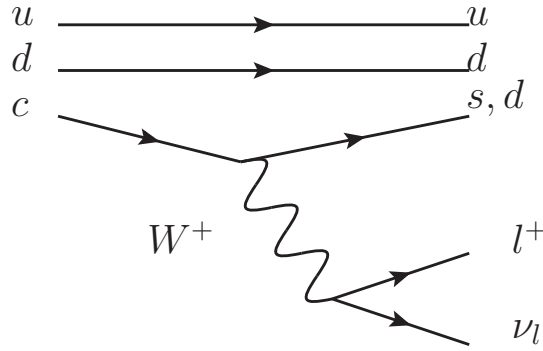


Figure 2.1: Semileptonic decay modes of the Λ_c^+ into a neutron (udd) or a Λ (uds), an positron or an anti-muon and the corresponding neutrino (own graphic)

W^\pm boson. The last fraction can be approximated through $-\frac{1}{m_W^2}$. The whole term becomes to $-\frac{g_w^2}{8m_W^2}$ and this is the Fermi coupling constant G_F except a factor $-\frac{1}{\sqrt{2}}$:

$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8m_W^2}$$

The weak decay has in this approximation a threesome vertex with the coupling constant G_F .

2.4 V-A current

The value of a vertex where two matching leptons transforms into a W^\pm boson is $-i\frac{g}{2\sqrt{2}}\gamma^\mu(1 - \gamma^5)$. 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

$$V_{CKM} = \begin{bmatrix} 0.97434_{-0.00012}^{+0.00011} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875_{-0.00033}^{+0.00032} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{bmatrix}. \quad (2.6)$$

With the general Feynman rules for vertices and propagators the transition matrix element becomes to (2.7) like in [12, Eq. 1].

$$T = \frac{G_F}{\sqrt{2}} V_{cq} \bar{u}_l \gamma^\mu (1 - \gamma^5) u_{\nu_l} \langle B(p', s') | J_\mu | \Lambda_c(p, s) \rangle \quad (2.7)$$

The B in (2.7) stands for the neutron or Λ . The current J_μ can be splitted in a vector and an axial-vector part $J_\mu = V_\mu - A_\mu$ like in (2.8).

$$\begin{aligned}\langle B(p', s') | V_\mu | \Lambda_c(p, s) \rangle &= \bar{u}(p', s') \left(F_1(q^2) \gamma_\mu + F_2(q^2) \frac{p_\mu}{m_{\Lambda_c}} + F_3(q^2) \frac{p'_\mu}{m_B} \right) u(p, s) \\ \langle B(p', s') | A_\mu | \Lambda_c(p, s) \rangle &= \bar{u}(p', s') \left(G_1(q^2) \gamma_\mu + G_2(q^2) \frac{p_\mu}{m_{\Lambda_c}} + G_3(q^2) \frac{p'_\mu}{m_B} \right) \gamma^5 u(p, s)\end{aligned}\quad (2.8)$$

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 methods

The **Sherpa** software use Monte-Carlo methods to calculate the decay widths and randomly select the dynamics of a process. In my thesis I did not work on the Monte-Carlo algorithms. For details about these methods the diploma[13] from Dr. Frank Siegert can be considered.

3 Methods and Implementation

3.1 Decays Data

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 deays. 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 $\Lambda_c^+ \rightarrow \Sigma(1385)^- + \pi^+ + \pi^+$ only the channel $\Sigma(1385) \rightarrow \Lambda + \pi$ was recognized. So a division with the $\text{BR}(\Sigma(1385) \rightarrow \Lambda + \pi)$ 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^+

Decay	BR(Delta BR)[Origin]	
	old	new
Modes with nucleons/Deltas		
$\Lambda_c^+ \rightarrow P^+ + K_b$	0.023(0.006)[PDG]	-
$\Lambda_c^+ \rightarrow P^+ + K_s$	-	0.0158(0.0008)[PDG]
$\Lambda_c^+ \rightarrow P^+ + K^- + \pi^+$	0.028(0.008)[PDG]	0.035(0.004)[PDG]
$\Lambda_c^+ \rightarrow P^+ + K_b + \pi$	0.033(0.010)[PDG]	0.0199(0.0013)[PDG]
$\Lambda_c^+ \rightarrow P^+ + \pi^+ + \pi^+ + \pi^- + \pi^-$	0.018(0.012)[PDG]	0.0023(0.0015)[PDG]
S = 0		
$\Lambda_c^+ \rightarrow P^+ + f(0980)$	0.0028(0.0019)[PDG]	0.0035(0.0023)[PDG]
S = 0		
$\Lambda_c^+ \rightarrow P^+ + \pi^+ + \pi^-$	0.0007(0.0007)[PDG]	-
S = 0		
$\Lambda_c^+ \rightarrow \Delta(1232)^{++} + K^-$	0.0086(0.003[PDG]	0.0109(0.0025)[PDG]
Modes with hyperons		
$\Lambda_c^+ \rightarrow \Lambda + \pi^+$	0.0107(0.0028)[PDG]	0.0130(0.0007)[PDG]

$\Lambda_c^+ \rightarrow \Lambda + \pi^+ + \pi$	-	0.071(0.0004)[PDG]
$\Lambda_c^+ \rightarrow \Lambda + \rho(770)^+$	-	0.036(0.013)[PDG]
S = 0		
$\Lambda_c^+ \rightarrow \Lambda + K^+$	0.0005(0.00016)[PDG]	0.00061(0.00012)[PDG]
$\Lambda_c^+ \rightarrow \Sigma^- + \pi^+ + \pi^+$	-	0.021(0.004)[PDG]
semileptonic modes		
$\Lambda_c^+ \rightarrow \Lambda + \nu_e + e^+$	0.021(0.006)[PDG]	0.036(0.004)[PDG]
$\Lambda_c^+ \rightarrow \Lambda + \nu_\mu + \mu^+$	0.020(0.007)[PDG]	0.036(0.004)[PDG]

In the case of $\Lambda_c^+ \rightarrow P^+ \pi^+ + \pi^-$ was the decay already included in $\Lambda_c^+ \rightarrow P^+ + f(0980)$. K_b was removed from the PDG and only K_s exists. For $\Lambda_c^+ \rightarrow \Lambda + \eta + \pi^+$ 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]	$\Lambda_c^+ \rightarrow n + \nu_e + e^+$
old	2112,14,-13	0.003[EvtGen]	$\Lambda_c^+ \rightarrow n + \nu_\mu + \mu^+$

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

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

In this notation is $q = p - p'$. A conversion 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 (2.8). 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)

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

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).

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

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.

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

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.

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

$$\begin{pmatrix} G_1 \\ G_2 \\ G_3 \end{pmatrix} = \begin{bmatrix} 1 & -\frac{3m_{\Lambda_c}-m_B}{4m_{\Lambda_c}} & \frac{m_{\Lambda_c}+m_B}{4m_B} \\ 0 & -1 & 1 \\ 0 & -\frac{m_B}{2m_{\Lambda_c}} & -\frac{m_B}{2m_{\Lambda_c}} \end{bmatrix} \cdot \begin{pmatrix} f_1^A \\ f_2^A \\ f_3^A \end{pmatrix} \quad (3.5)$$

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

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

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 .

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

The definition of L_μ is given in [13, Eq. A.96] and the Y in [13, Eq. A.94]. They are visible again in (3.9).

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

The projection operators that are used in (3.9) are defined in (3.10)

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

This all equations together form a current wich is similiar to {(2.8)}. 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).

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

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

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

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[8] was considered and for $n + l^+ + \nu_l$ the paper[7]. The parametrization of the form factor is given by (3.13)

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

The parameters $F(0)$, a and b are taken from the numerical results of [8].

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 [10]. The parametriza-

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

$$\begin{aligned}
F &= (a_0 + a_2 q^2 + a_4 q^4) e^{-\frac{3m_\sigma^2 p_\Lambda^2}{2m_\Lambda^2 \alpha_{\lambda\lambda'}}} \\
p_\Lambda &= \frac{1}{2m_\Lambda} \lambda^{\frac{1}{2}}(m_{\Lambda_c}^2, m_\Lambda^2, q^2) \\
\lambda(x, y, z) &= x^2 + y^2 + z^2 - 2xy - 2yz - 2zx (\text{triangle function}) \\
\alpha_{\lambda\lambda'} &= \sqrt{\frac{\alpha_\lambda^2 + \alpha_{\lambda'}^2}{2}}
\end{aligned} \tag{3.14}$$

In equation(3.14) is m_σ the mass of the light quark obtained from [10, p. 13/I] and the α_λ are size parameters of the baryons from [10, 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 [9] computed. The parametrization(3.15) is through the same values for the first two axial-vector and vector form factors very simple

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

$f_i(0)$, 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 semileptonic transitions into n as well as into Λ . The parametrization(3.16) was done until a very high order of the q^2 .

$$F(q^2) = \frac{F(0)}{1 - \sigma_1 s + \sigma_2 s^2 + \sigma_3 s^3 + \sigma_4 s^4} \text{ with } s = \frac{q^2}{m_{\Lambda_c}^2} \tag{3.16}$$

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 used 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

4.1 Decay table

The decays of the Λ_c^+ was simulated with the old and the new decay tables. 100000000 decay events were used. This leads to a low statistic uncertainty. This section should show the impact of my changes in decay tables. Selected inclusive modes are used to show the difference. The observables multiplicity and energy are used for the comparison. The multiplicity is the number of a specific particles that is created during the process. The energy is measured by the squared four-momentum of the particle.

The figures in the following section can also be found in the appendix A.2. These figures only show the measurement of the particles after the primary decay of the Λ_c^+ . The figures for the measurement at the final state of the decay chain are in A.3.

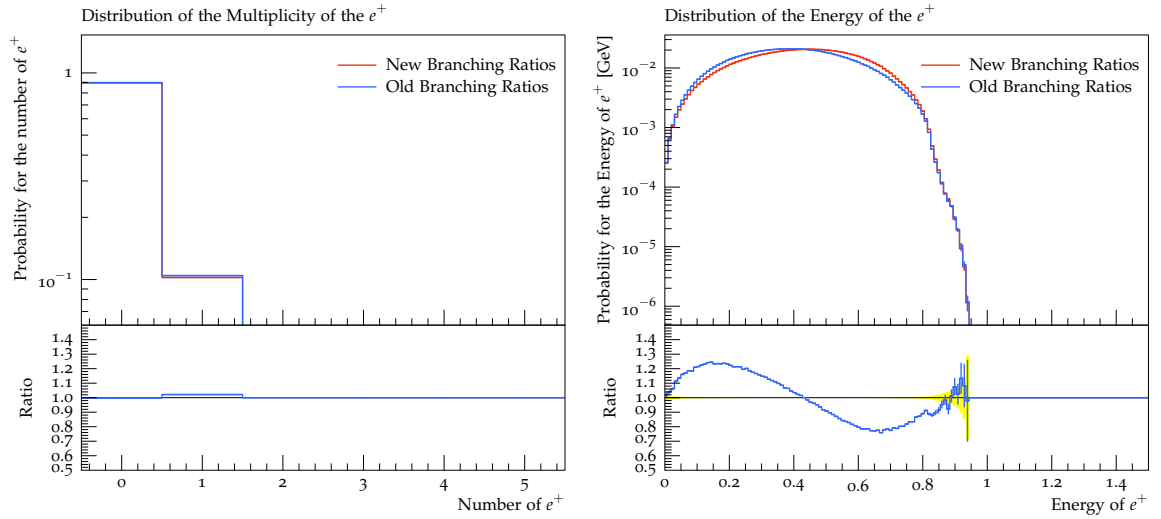


Figure 4.1: multiplicity and energy spectrum of the e^+

In figures 4.1 and 4.2 you can see that the change of the branching ratios of the semileptonic decays resulting in a nearly equal multiplicity distribution but a significant different energy spectrum for both leptons. The cut-off at the beginning of the muon energy spectrum comes from the bigger rest mass than the electron. This energy is needed to create a detectable on-shell muon.

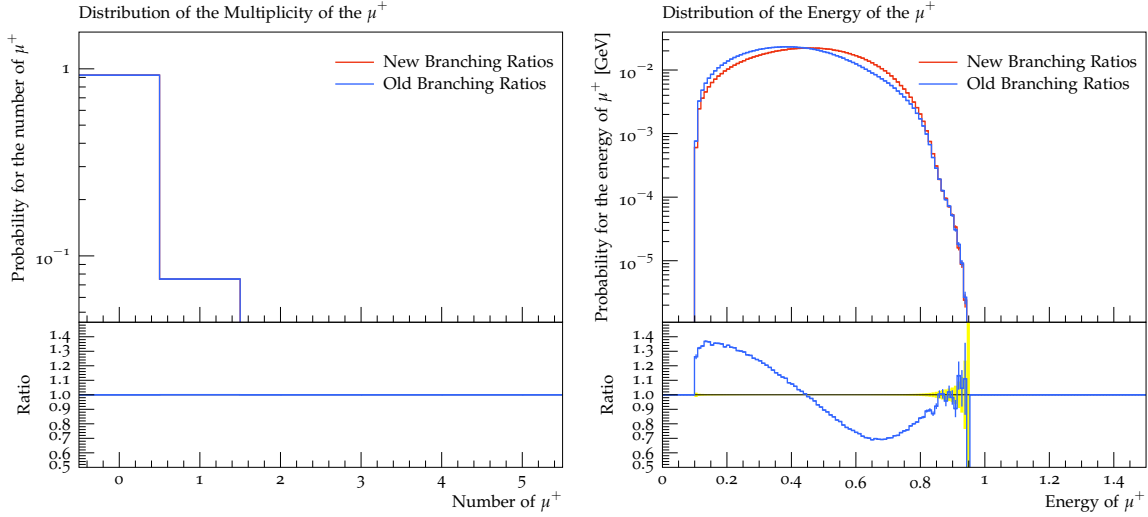


Figure 4.2: multiplicity and energy spectrum of the μ^+

The two main processes to create leptons are the semileptonic decays

$$\Lambda_c^+ \rightarrow \Lambda + l^+ + \nu_l$$

and

$$\Lambda_c^+ \rightarrow n + l^+ + \nu_l.$$

Only the branching ratios for the process with the Λ in the final state were changed. The higher rest mass of the Λ compared to the neutron leads to leptons with a lower energy. The branching ratio for the Λ were increased. The branching ratio for the neutron is the same as before. The Increase of the branching ratio is visible as the energy shift in the energy spectrum. The multiplicity didn't changed much because both processes have the same multiplicity. The probability for one positron becomes a little lower. This leads from the lower increase of the branching ratio of the electron compared to the muon.

These changes in the primary decay leads also to changes in the further decays. The figures for the measurement of the particles after the whole decay chain in A.3 look really the same. The plots 4.3 from the π^+ show drastic changes. This changes will be discussed in the following paragraph. Due to the update of the decay table the probability for multiplicity zero and one processes becomes equal. This leads mainly from the processes

$$\Lambda_c^+ \rightarrow \Sigma(1385)^+ + \pi^+ + \pi^-$$

and

$$\Lambda_c^+ \rightarrow \Sigma + \pi^+.$$

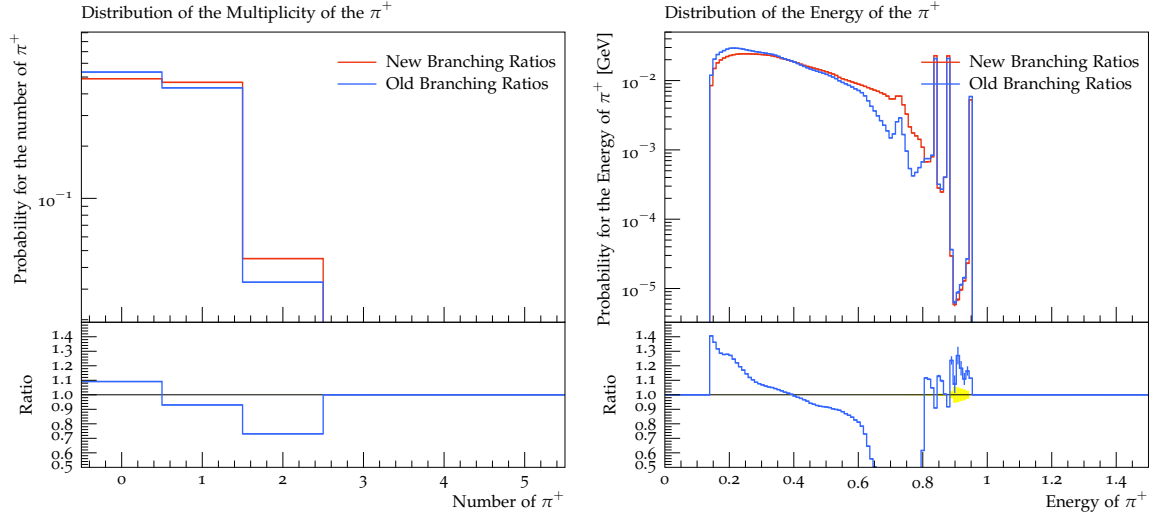


Figure 4.3: multiplicity and energy spectrum of the π^+

In these processes one π^+ is created and both branching ratios has been increased. This explains the increase of the probability for the production of on pion.

The decay channel

$$\Lambda_c^+ \rightarrow \Sigma^- + \pi^+ + \pi^+$$

was added to the decay table. This process leads to the increase of the probability for pion multiplicity two.

The new decay channel

$$\Lambda_c^+ \rightarrow \Lambda + \pi^+ + \pi$$

is the reason why the gap near 0.7 GeV is filled. It is the only reason for this change because in 4.9 happens the same thing for the π . And the only new process with a π^+ and a π in the final state is the process

$$\Lambda_c^+ \rightarrow \Lambda + \pi^+ + \pi$$

The peaks in the energy spectrum can be identified with specific decay channels. This channels are $1 \rightarrow 2$ processes because in such a process the dynamics of the end products is well determined due to momentum conversation. The peak with the highest energy is obtained from

$$\Lambda_c^+ \rightarrow n + \pi^+$$

because the proton have the lowest mass from all products of $1 \rightarrow 2$ processes with a π^+ in

the final state. The second peak comes from

$$\Lambda_c^+ \rightarrow \Lambda + \pi^+,$$

the third from

$$\Lambda_c^+ \rightarrow \Sigma + \pi^+$$

and the fourth from

$$\Lambda_c^+ \rightarrow \Delta(1232) + \pi^+.$$

The peak from the $\Delta(1232)$ is at the lowest position because the mass of this particle is the highest compared to the others.

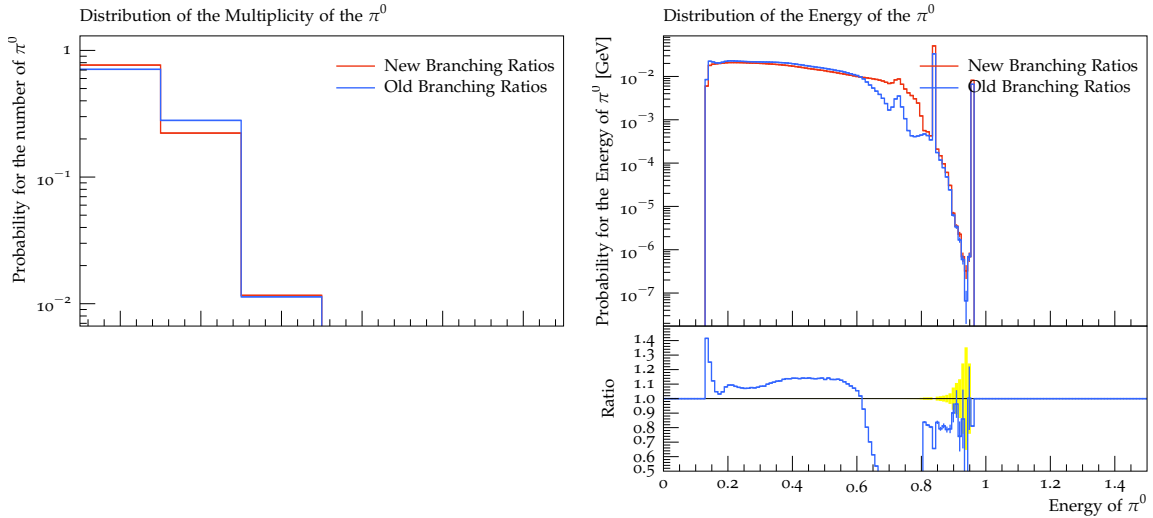


Figure 4.4: multiplicity and energy spectrum of the π

The diagram 4.9 is very similar to 4.3. For a complete decay chain A.3 the distribution for the π disappears because it is unstable.

In the further consideration only the other end product for $1 \rightarrow 2$ process that leads to a peak is used to characterize the decay. This is simpler and the other end product will always be the regarded particle of the energy spectrum. The other end product besides the π has to be a positive charged particle. The family of baryons for the decay will be the same only a charged particle is picked up. For the Λ baryons exist only the Λ_t^+ besides the Λ_c^+ with a positive charge. Both are no decay candidates because their masses are too high. So at this position there will be no peak. The peaks from the right to the left results from the following decays: n , Σ^+ , $\Delta(1232)^+$. The diagram 4.5 shows only little changes. No decay channels with a K^+ in the final state were added and so this result is expected. Due to the masses of the other particle in the final state the peaks can be connected to the different decay channels. From

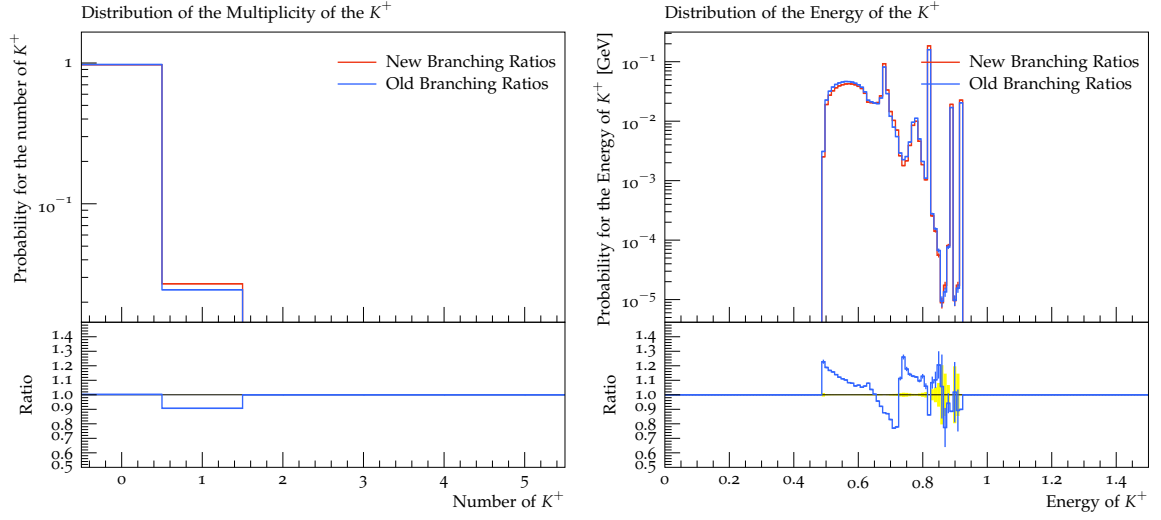


Figure 4.5: multiplicity and energy spectrum of the K^+

right to the left the peaks results from $1 \rightarrow 2$ decays with a Λ , Σ , Ξ , $\Sigma(1385)$ or a $\Xi(1530)$ and a K^+ in the final state. The events that are missed in 4.6 are in 4.7 because the process

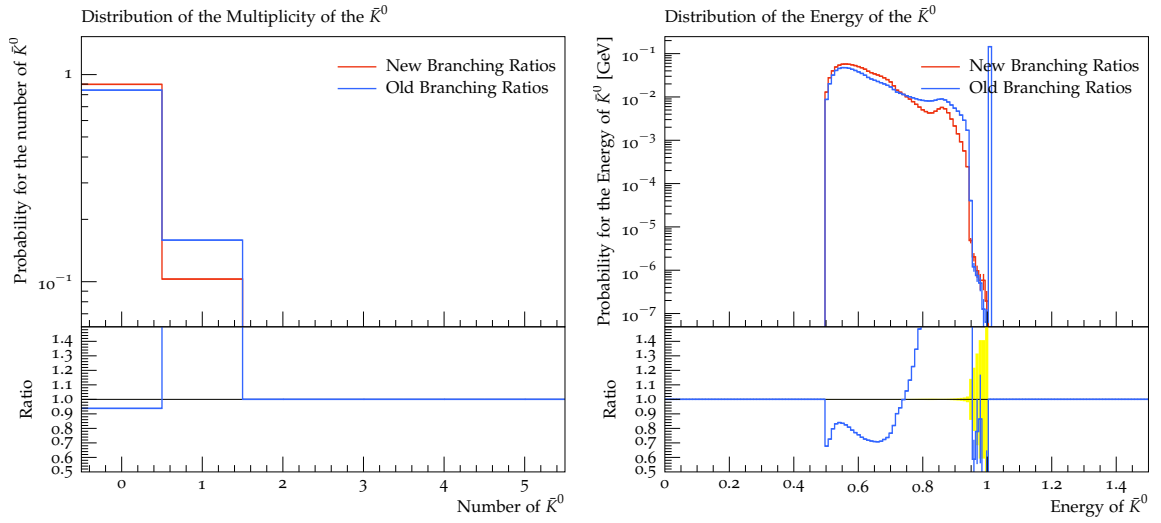


Figure 4.6: multiplicity and energy spectrum of the \bar{K}

$$\Lambda_c^+ \rightarrow P^+ + K_b$$

was changed to

$$\Lambda_c^+ \rightarrow P^+ + K_s$$

. The process

$$\Lambda_c^+ \rightarrow P^+ + K_s + \pi^+ + \pi^-$$

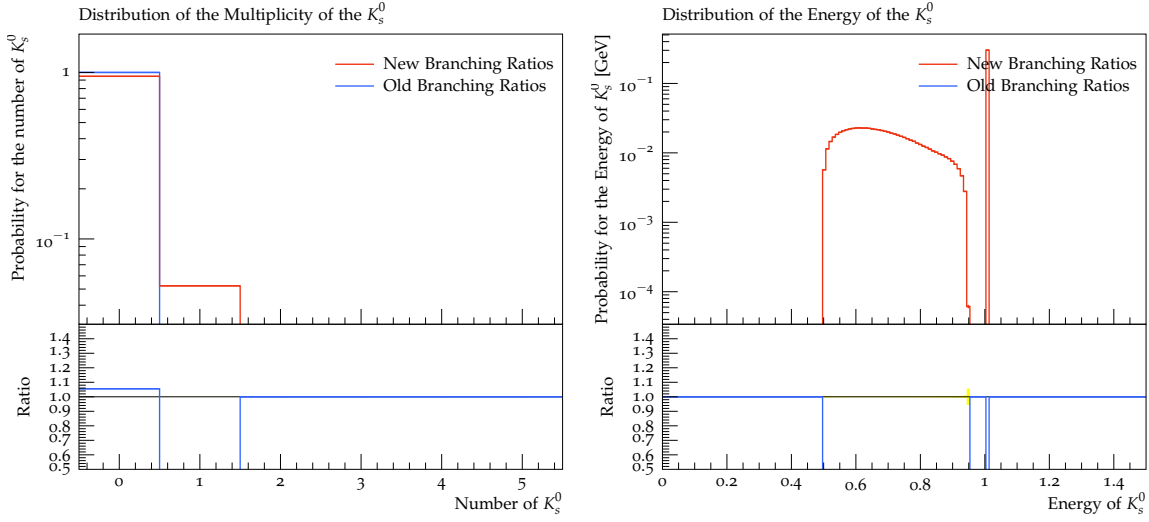


Figure 4.7: multiplicity and energy spectrum of the K_s

was added as a decay channel. This leads to the distribution in the two diagrams. The peak in 4.7 belongs to the proton. The $1 \rightarrow 2$ decays with a Σ^+ is the reason for the high isolated

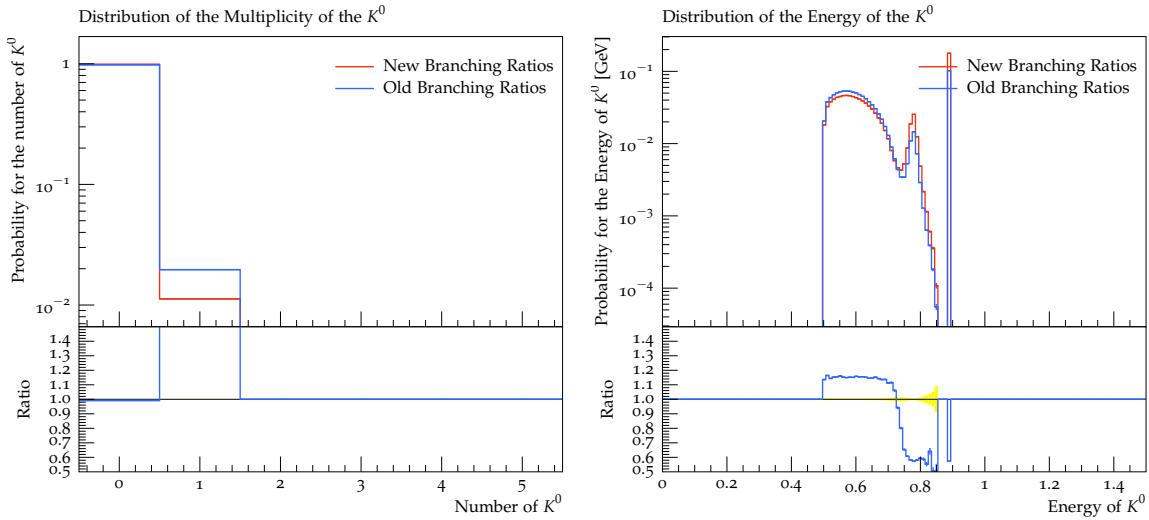


Figure 4.8: multiplicity and energy spectrum of the K

peak and $\Sigma(1385)^+$ for the peak on the hill. The diagrams are changed slightly because the branching ratios were changed. They were decreased. The decrease of the process

$$\Lambda_c^+ \rightarrow P^+ + \pi^+ + \pi^+ + \pi^- + \pi^-$$

has a dramatic impact on the multiplicity diagram because it is the only process that produces two π^- . The red bulge is a superposition of all little changes because no processes were changed so drastically.

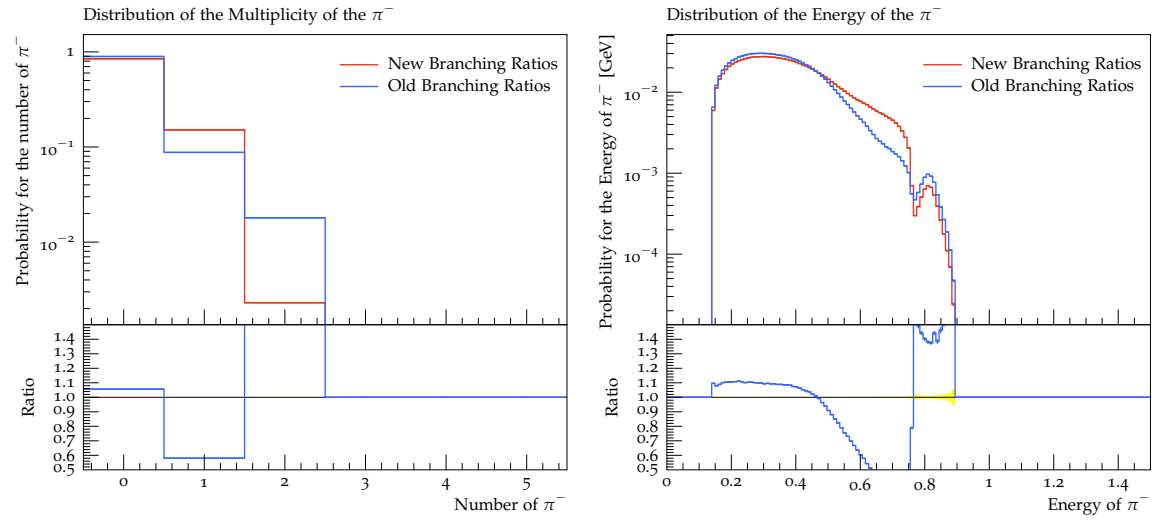


Figure 4.9: multiplicity and energy spectrum of the π^-

4.2 Form Factor Models

4.2.1 $\Lambda_c^+ \rightarrow \Lambda + l^+ + \nu_l$

All diagrams of the form factors show the same behavior. There is no difference in the semileptonic decays in electron or muon except of a sharp increase of the beginning of the graph for the muon. But this comes from the higher mass of the muon compared to the electron.

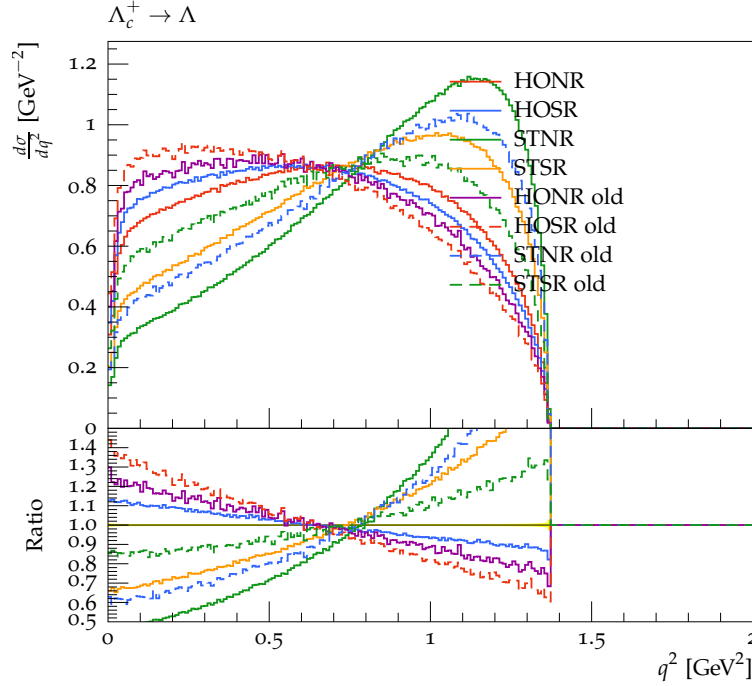


Figure 4.10: Comparison from the already implemented form factor models in leading order (old) and with all factors for Λ

The diagram (4.10) shows that influence of the higher form factors is for this model not neglectable. So it is important to uncomment the Y function of (3.9) in VA_B_B.C. This will be obtain more accurate results because the author of these models make his calculations with all terms and not only with the leading order form factors. The deviations among themselves are very impressive. The harmonic oscillator ones have generally a more flat run in contrast to the Sturmian ones with a linear increase and then a sharp decline.

The both parametrization for the light-cone sum rule in (4.11) for different twist show the similar properties. Twist 6 looks like that the steep ascent will increase with a higher twist number but without more calculations with higher twist numbers it is only a theory.

The behavior of the different parametrization (4.12) of the QCD sum rule model is for the two classes of parametrizations very different. The pole parametrizations themselves are very similar. They only have little deviations. The general curve is flat and has no small maximum. The complete parametrizations on the other hand have a clear maximum and a more steep slope. The full parametrization with the continuum model triangular and $\kappa = 2$ is an exception.

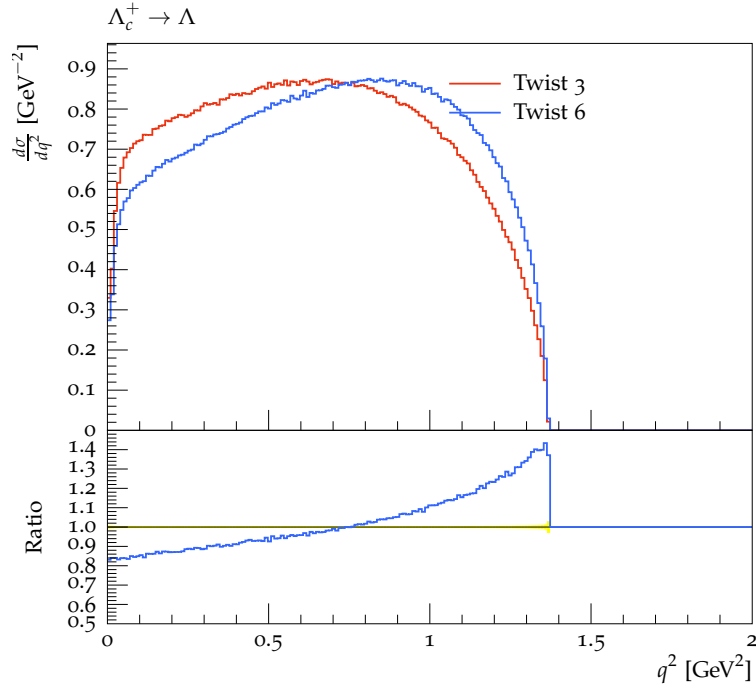


Figure 4.11: Comparison from the different parametrization of the LCSR model for Λ

This one describes more the transition between the parametrizations.

The diagram (4.13) shows the big differences between the difference models. The spread between the curves is very high and experimental data is needed to really compare this data and select the right form factor model.

The CCQM and the RQM are very similar.

In (4.14) is a comparison with the original implemented form factor models. The LCSR have an analogical like the HONR.

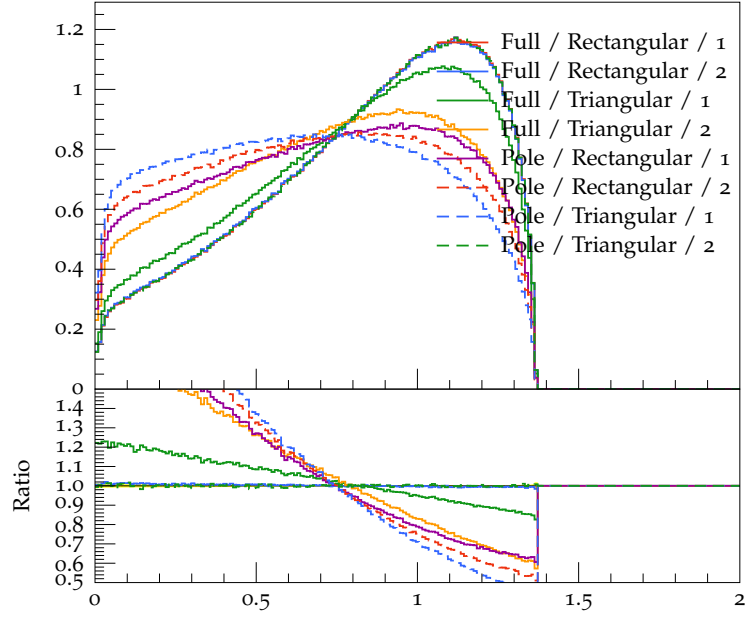


Figure 4.12: Comparison from the different parametrization of the QCDSR model for Λ

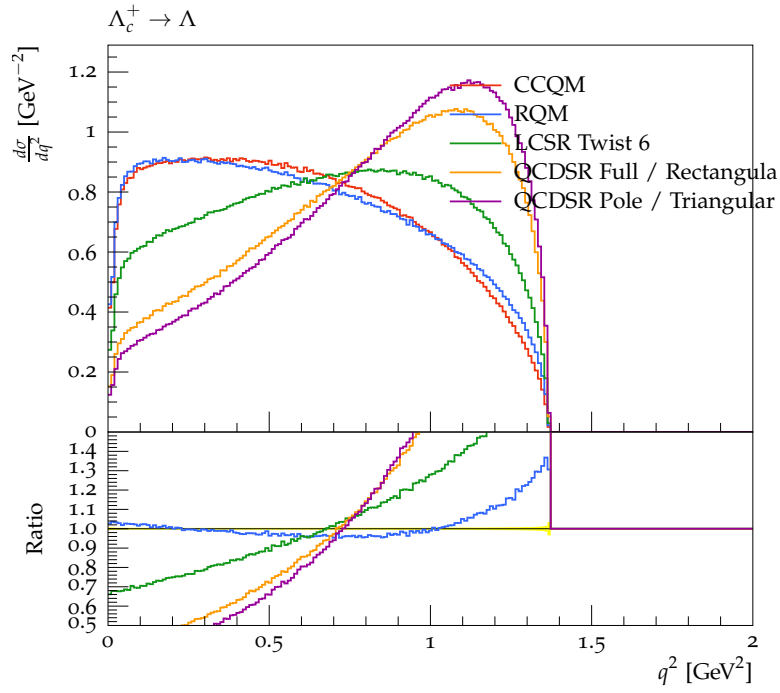


Figure 4.13: Comparison from some of the self implemented form factor models for Λ

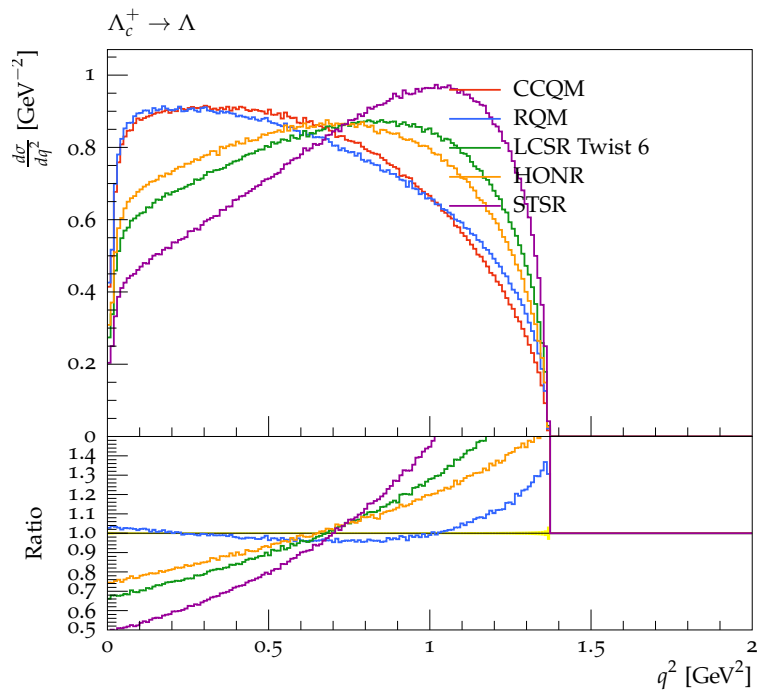


Figure 4.14: Comparison from the already implemented form factor models with some of the self implemented ones for Λ

4.2.2 $\Lambda_c^+ \rightarrow n + l^+ + \nu_l$

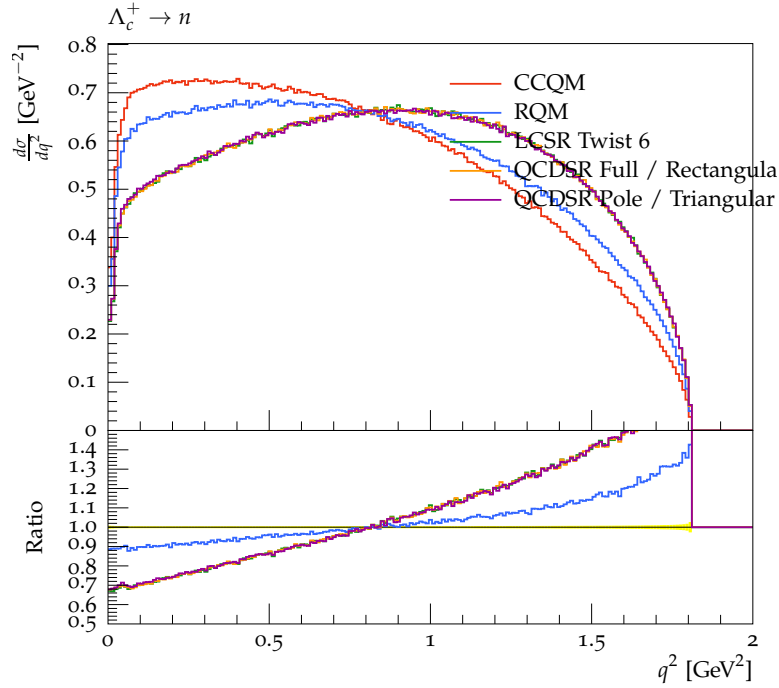


Figure 4.15: Comparison from some of the self implemented form factor models for the neutron

The form factor models (4.15) shows in general a more flat run. Only the CCQM and the RQM have an computation for the neutron. The other models were used with the harmonic oscillator semi relativistic model (HOSR). This model was the previous default. Important to register is that through the lower mass of the neutron the bigger range has to be discribed by the model.

This (4.16) is a comparison of all four form factor models for the neutron because for LCSR and STSR the HOSR is used. The models for the neutron didn't have such big deviations like the ones for the Λ . So the choice of the model is for the neutron not so important because all of this will give similar results.

And so the concentration should lay on the Λ . But without good experimental datas a clean comparison is not possible and so no model can be preferred.

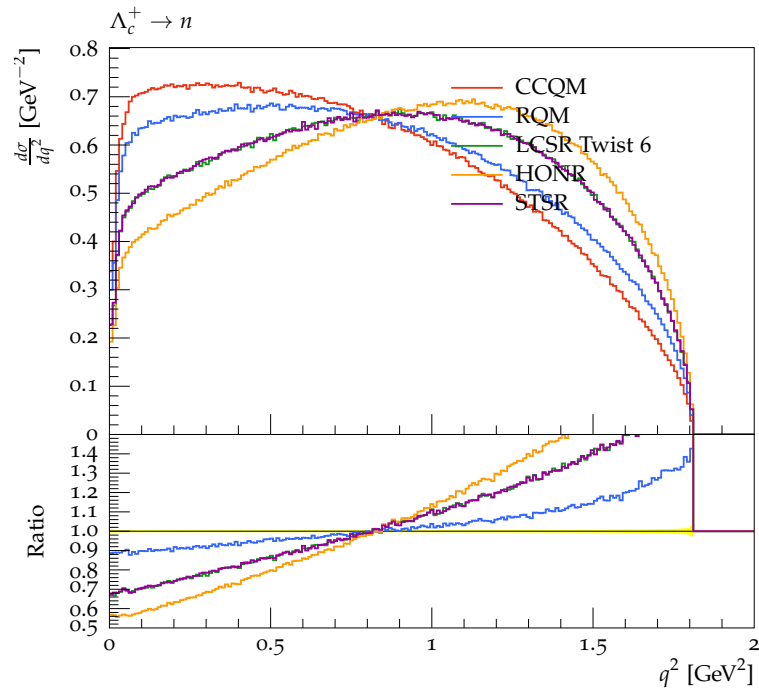


Figure 4.16: Comparison from the already implemented form factor models with some of the self implemented ones for the neutron

5 Summary and Outlook

This bachelor thesis gave a little contribution to world biggest experiment through the update of the branching ratios of the Λ_c^+ . Every Baryon is important because with everyone the modeling of the processes in the nature becomes more accurate. Through more exact modeling the comparison between our laws of nature, in this special case the standard model of particle physics, and the reality becomes better and better again. So discrepancies are discoverable and the theory can be improved.

This work shows that the position of the peaks in the energy spectrum are correlated to the masses of the other particles in the final state. These peaks occur only with two particles in the final state. This comes from the determination of the four-momentum in this case. The particles have no other choice to put the momentum elsewhere.

There exists a lot of different form factor models and the behavior of them can partially vary differently, flat or steep run, only a comparison with experimental data can clarify. This leads to a lot of measurements because every particle has a slightly different behavior when it decays. But only with these amount of data a clear answer for every particle is possible.

The non relativistic quark model [10] was introduced and implemented with this thesis in **Sherpa**. For the excited Λ states didn't exist so much experimental data. The concentration has layed on the other models because it would be easier to get data. But as a continuation to this work this model can be tested. Further an implementation of the form factor model from Lattice QCD [11] would be a great work. The Lattice QCD is a modern method of the QCD and used in many aspects.

6 Bibliography

- [1] R. S. Marques de Carvalho et al. “Form factors and decay rates for heavy Λ semileptonic decays from QCD sum rules”. In: *Phys. Rev. D* 60 (3 1999), p. 034009. DOI: 10.1103/PhysRevD.60.034009. URL: <https://link.aps.org/doi/10.1103/PhysRevD.60.034009>.
- [2] A. Ceccucci (CERN), Z. Ligeti (LBNL), and Y. Sakai (KEK). *THE CKM QUARK-MIXING MATRIX*. 2016. URL: <http://pdg.lbl.gov/2016/reviews/rpp2016-rev-ckm-matrix.pdf> (visited on 03/27/2017).
- [3] C. Patrignani et al.(Particle Data Group). *CHARMED BARYONS Λ_c^+* . 2016. URL: <http://pdglive.lbl.gov/Particle.action?node=S033&init=> (visited on 03/09/2017).
- [4] R. N. Faustov and V. O. Galkin. “Semileptonic decays of Λ_b baryons in the relativistic quark model”. In: *Phys. Rev. D* 94 (7 2016), p. 073008. DOI: 10.1103/PhysRevD.94.073008. URL: <https://link.aps.org/doi/10.1103/PhysRevD.94.073008>.
- [5] R. N. Faustov and V. O. Galkin. “Semileptonic decays of Λ_c baryons in the relativistic quark model”. In: *Eur. Phys. J. C* 76.11 (2016), p. 628. DOI: 10.1140/epjc/s10052-016-4492-z. arXiv: 1610.00957 [hep-ph].
- [6] T. Gleisberg et al. “Event generation with SHERPA 1.1”. In: *JHEP* 02 (2009), p. 007. DOI: 10.1088/1126-6708/2009/02/007. arXiv: 0811.4622 [hep-ph].
- [7] Thomas Gutsche et al. “Heavy-to-light semileptonic decays of Λ_b and Λ_c baryons in the covariant confined quark model”. In: *Phys. Rev. D* 90.11 (2014). [Erratum: *Phys. Rev. D* 94,no.5,059902(2016)], p. 114033. DOI: 10.1103/PhysRevD.90.114033, 10.1103/PhysRevD.94.059902. arXiv: 1410.6043 [hep-ph].
- [8] Thomas Gutsche et al. “Semileptonic decays $\Lambda_c^+ \rightarrow \Lambda \ell^+ \nu_\ell$ ($\ell = e, \mu$) in the covariant quark model and comparison with the new absolute branching fraction measurements of Belle and BESIII”. In: *Phys. Rev. D* 93.3 (2016), p. 034008. DOI: 10.1103/PhysRevD.93.034008. arXiv: 1512.02168 [hep-ph].
- [9] Ming-Qiu Huang and Dao-Wei Wang. “Semileptonic decay $\Lambda_b(c) \rightarrow \Lambda_b l + \nu$ from QCD light-cone sum rules”. In: (2006). arXiv: hep-ph/0608170 [hep-ph].

-
- [10] Md Mozammel Hussain and Winston Roberts. “ Λ_c Semileptonic Decays in a Quark Model”. In: *Phys. Rev. D* 95.5 (2017). [Addendum: *Phys. Rev. D* 95, no. 9, 099901 (2017)], p. 053005. DOI: 10.1103/PhysRevD.95.099901, 10.1103/PhysRevD.95.053005. arXiv: 1701.03876 [nucl-th].
 - [11] Stefan Meinel. “ $\Lambda_c \rightarrow \Lambda l^+ \nu_l$ ”. In: *Phys. Rev. Lett.* 118 (8 2017), p. 082001. DOI: 10.1103/PhysRevLett.118.082001. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.118.082001>.
 - [12] Muslema Pervin, Winston Roberts, and Simon Capstick. “Semileptonic decays of heavy lambda baryons in a quark model”. In: *Phys. Rev. C* 72 (2005), p. 035201. DOI: 10.1103/PhysRevC.72.035201. arXiv: nucl-th/0503030 [nucl-th].
 - [13] Frank Siegert. “Simulation of hadron decays in SHERPA”. In: (2007).

A Appendix

A.1 Decays.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]	$\Lambda_c^+ \rightarrow P^+ + K_b$
new	2212,310	0.0158(0.0008)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K_s$
old	2212,-313	0.016(0.005)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^*(892)_b$
new	2212,-313	0.0198(0.0028)[PDG]	
old	2212,-321,211	0.028(0.008)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^- + \pi^+$
new	2212,-321,211	0.035(0.004)[PDG]	
old	2212,-311,111	0.033(0.010)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K_b + \pi$
new	2212,310,111	0.0199(0.0013)[PDG]	
old	2212,-311,221	0.012(0.004)[PDG]	$\Lambda_c^+ \rightarrow P^+ K_b + \eta$
new	2212,-311,221	0.016(0.004)[PDG]	
old	2212,-311,211,-211	0.026(0.007)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K_b + \pi^+ + \pi^-$
new	2212,-311,211,-211	0.049(0.004)[PDG]	
created	2212,310,211,-211	0.0166(0.0012)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K_s + \pi^+ + \pi^-$
old	2212,-323,211	0.016(0.005)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^*(892)_b^+ + \pi^+$
new	2212,-323,211	0.015(0.005)[PDG]	
old	2212,-321,211,111	0.036(0.012)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^- + \pi^+ + \pi$
new	2212,-321,211,111	0.046(0.09)[PDG]	
old	2212,-321,211,211,-211	0.0011(0.0008)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^- + \pi^+ + \pi^+ + \pi^-$
new	2212,-321,211,211,-211	0.0014(0.001)[PDG]	
old	2212,-321,211,111,111	0.008(0.004)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^- + \pi^+ + \pi + \pi$
new	2212,-321,211,111,111	0.01(0.005)[PDG]	
old	2212,333	0.00082(0.00027)[PDG]	$\Lambda_c^+ \rightarrow P^+ + \phi(1020)$
new	2212,333	0.00104(0.00021)[PDG]	
S = 0			

old	2212,321,-321	0.00035(0.00017)[PDG]	$\Lambda_c^+ \rightarrow P^+ + K^+ + K^-$
new	2212,321,-321	0.00044(0.00018)[PDG]	
S = 0			
old	2212,211,211,-211,-211	0.018(0.012)[PDG]	$\Lambda_c^+ \rightarrow P^+ + \pi^+ + \pi^+ + \pi^- + \pi^-$
new	2212,211,211,-211,-211	0.0023(0.0015)[PDG]	
S = 0			
old	2212,9010221	0.0028(0.0019)[PDG]	$\Lambda_c^+ \rightarrow P^+ + f(0980)$
new	2212,9010221	0.0035(0.0023)[PDG]	
S = 0			
deleted	2212,211,-211	0.0007(0.0007)[PDG]	$\Lambda_c^+ \rightarrow P^+ + \pi^+ + \pi^-$
S = 0			
old	2224,-321	0.0086(0.003)[PDG]	$\Lambda_c^+ \rightarrow \Delta(1232)^{++} + K^-$
new	2224,-321	0.0109(0.0025)[PDG]	
Modes with hyperons			
old	3122,211	0.0107(0.0028)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + \pi^+$
new	3122,211	0.0130(0.0007)[PDG]	
created	3122,211,111	0.071(0.0004)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + \pi^+ + \pi$
created	3122,213	0.036(0.013)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + \rho(770)^+$
S = 0			
old	3122,321	0.0005(0.00016)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + K^+$
new	3122,321	0.00061(0.00012)[PDG]	
old	3122,211,113	0.011(0.005)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + \pi^+ + \rho(770)$
new	3122,211,113	0.015(0.006)[PDG]	
old	3122,221,211	0.018(0.006)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + \eta + \pi^+$
new	3122,221,211	0.022(0.005)[PDG]	
old	3122,223,211	0.018(0.006)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + \omega(782) + \pi^+$
new	3122,223,211	0.015(0.005)[PDG]	
old	3122,321,-311	0.0047(0.0015)[PDG]	$\Lambda_c^+ \rightarrow \Lambda + K^+ + K_b$
new	3122,321,-311	0.0057(0.0011)[PDG]	
old	3114,211,211	0.0055(0.0017)[PDG]	$\Lambda_c^+ \rightarrow \Sigma(1385)^- + \pi^+ + \pi^+$
new	3114,211,211	0.0090(0.0018)[PDG]	
created	3112,211,211	0.021(0.004)[PDG]	$\Lambda_c^+ \rightarrow \Sigma^- + \pi^+ + \pi^+$
old	3212,211	0.0105(0.0028)[PDG]	$\Lambda_c^+ \rightarrow \Sigma + \pi^+$
new	3212,211	0.0129(0.0007)[PDG]	
S = 0			
old	3212,321	0.00042(0.00013)[PDG]	$\Lambda_c^+ \rightarrow \Sigma + K^+$

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

A.2 Primary Decays

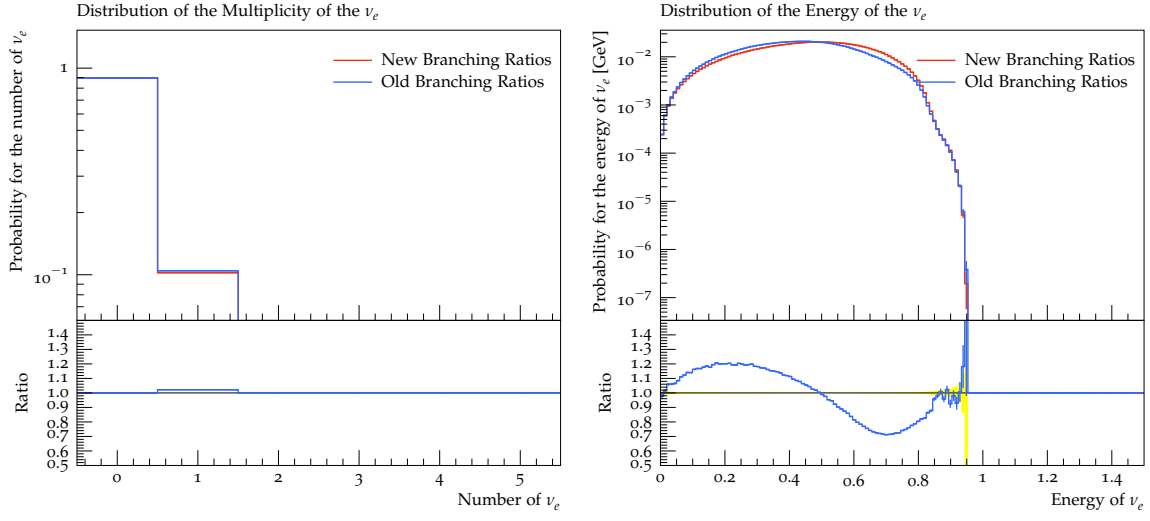


Figure A.1: multiplicity and energy spectrum of the ν_e

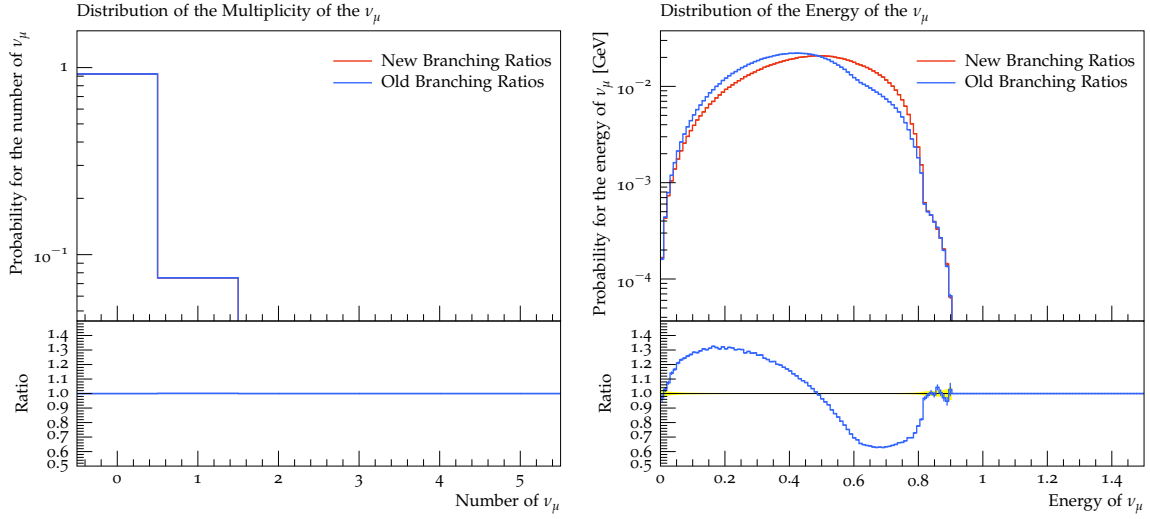


Figure A.2: multiplicity and energy spectrum of the ν_μ

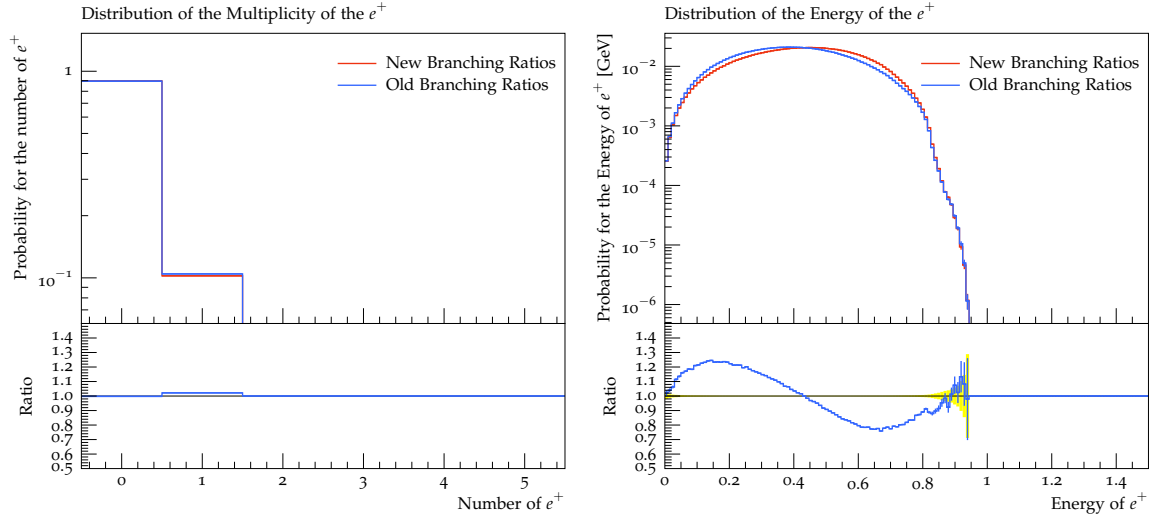


Figure A.3: multiplicity and energy spectrum of the e^+

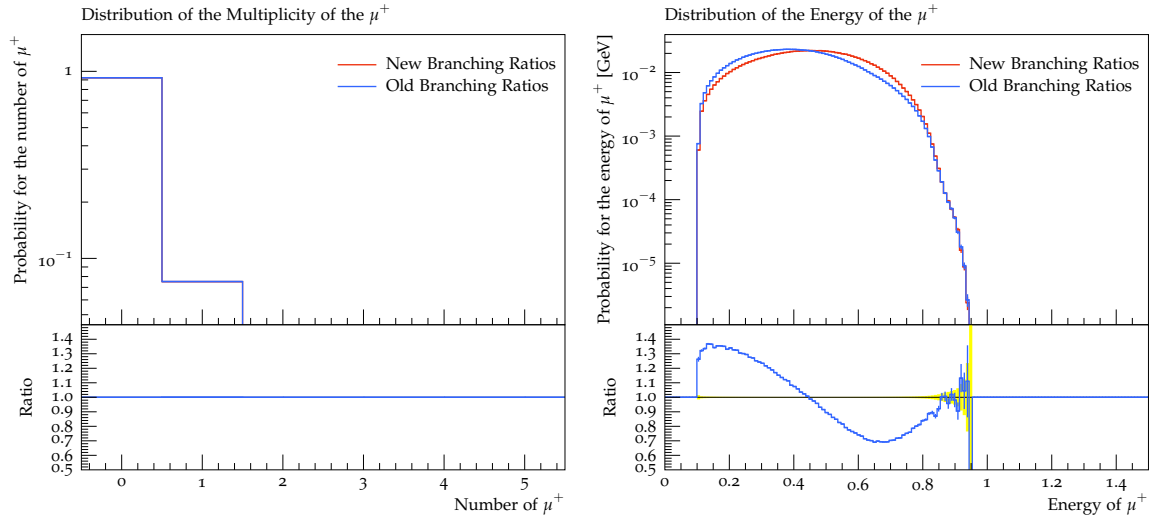


Figure A.4: multiplicity and energy spectrum of the μ^+

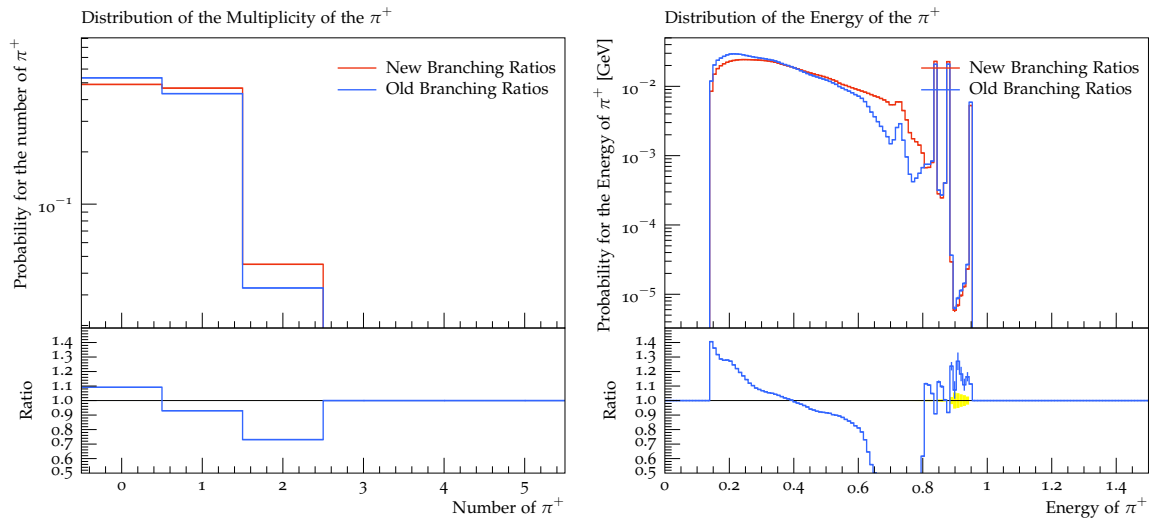
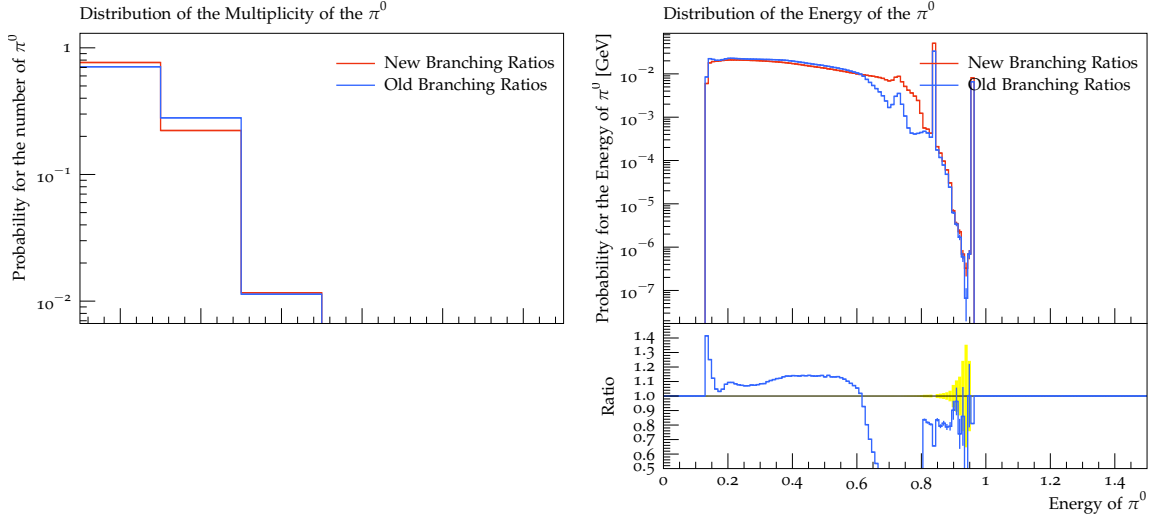
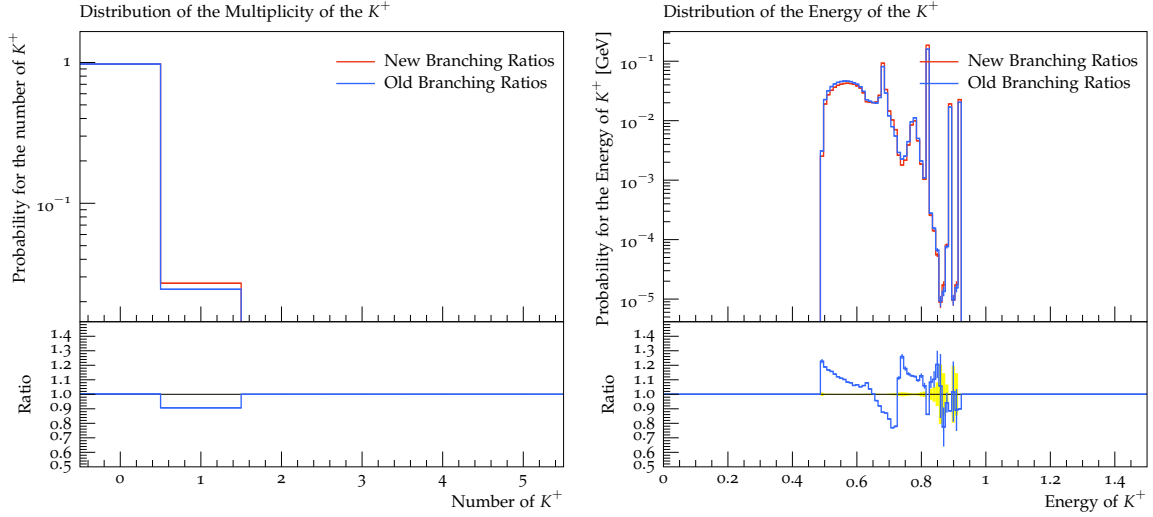
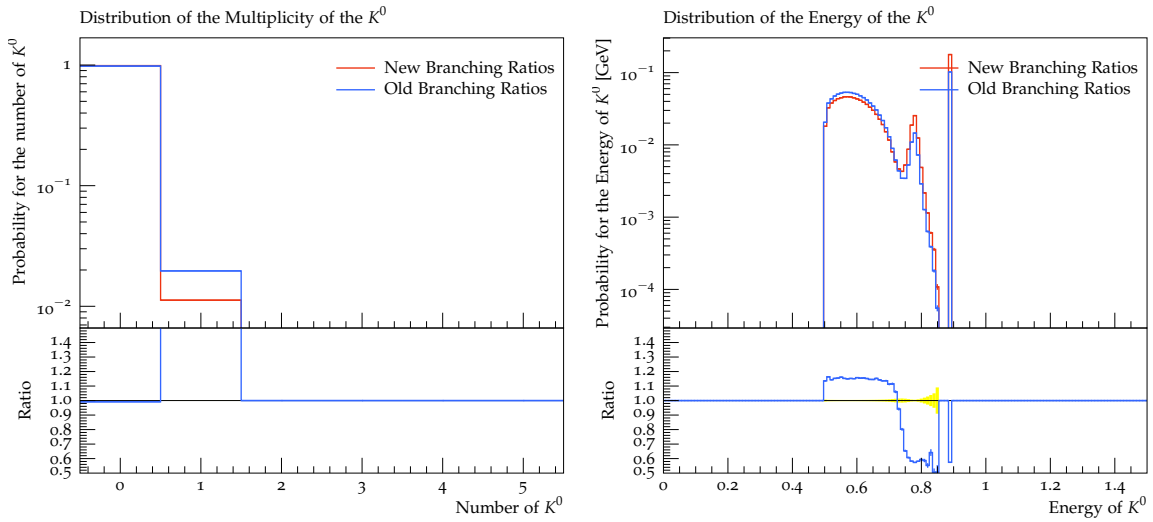


Figure A.5: multiplicity and energy spectrum of the π^+

Figure A.6: multiplicity and energy spectrum of the π Figure A.7: multiplicity and energy spectrum of the K^+ Figure A.8: multiplicity and energy spectrum of the K

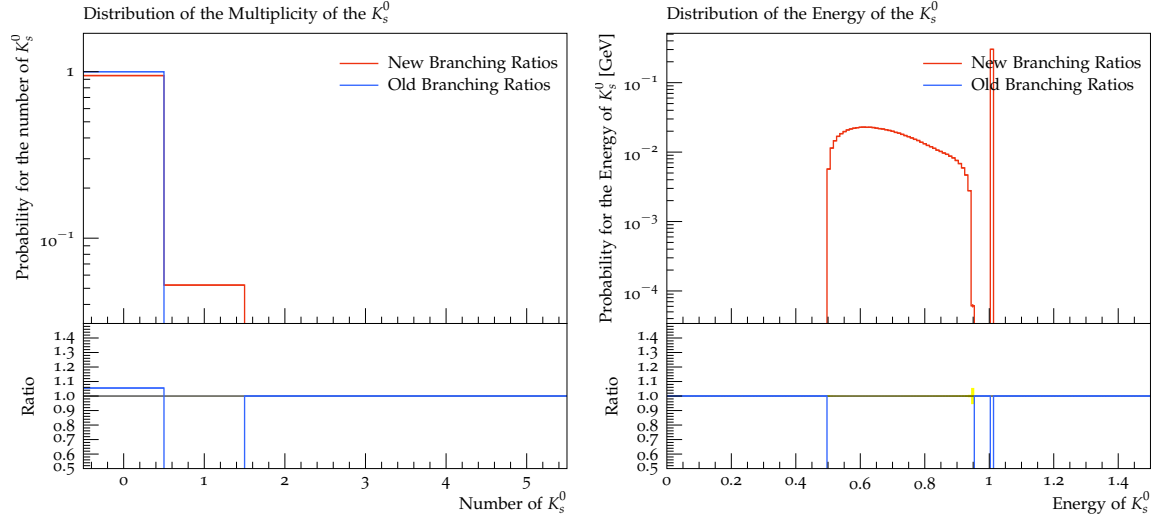


Figure A.9: multiplicity and energy spectrum of the K_s

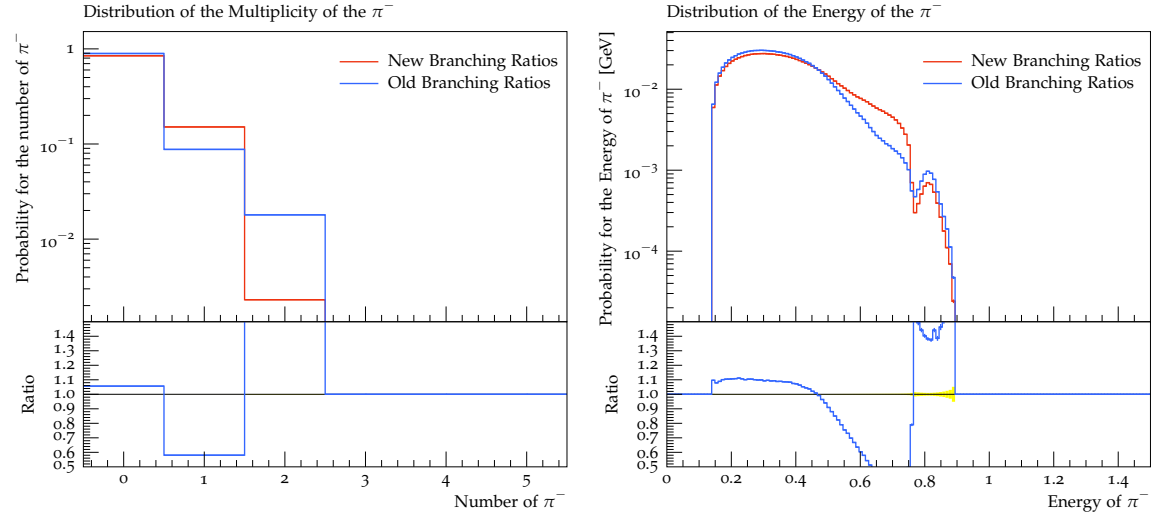


Figure A.10: multiplicity and energy spectrum of the π^-

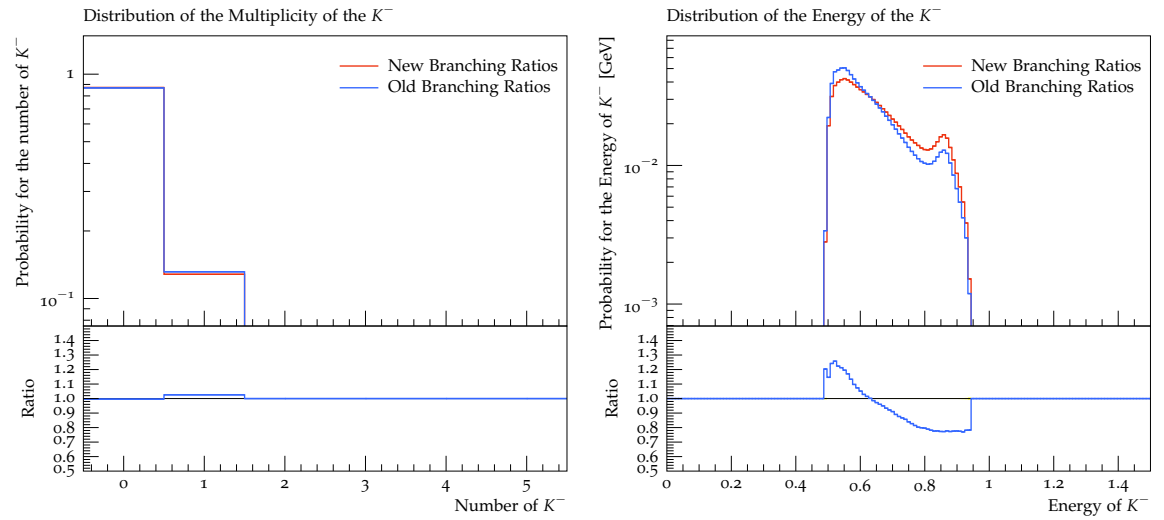


Figure A.11: multiplicity and energy spectrum of the K^-

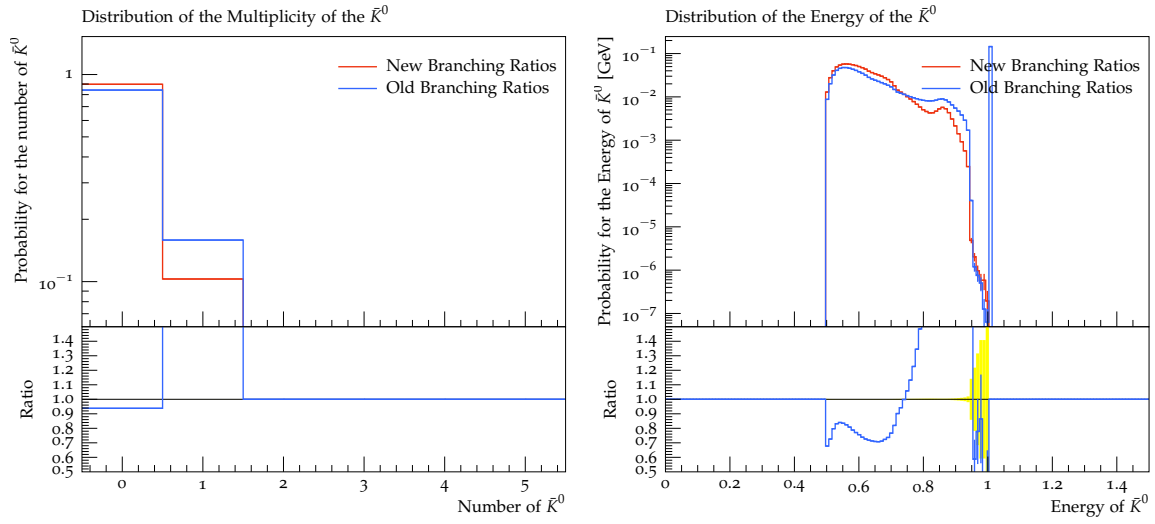


Figure A.12: multiplicity and energy spectrum of the \bar{K}

A.3 Complete Decays

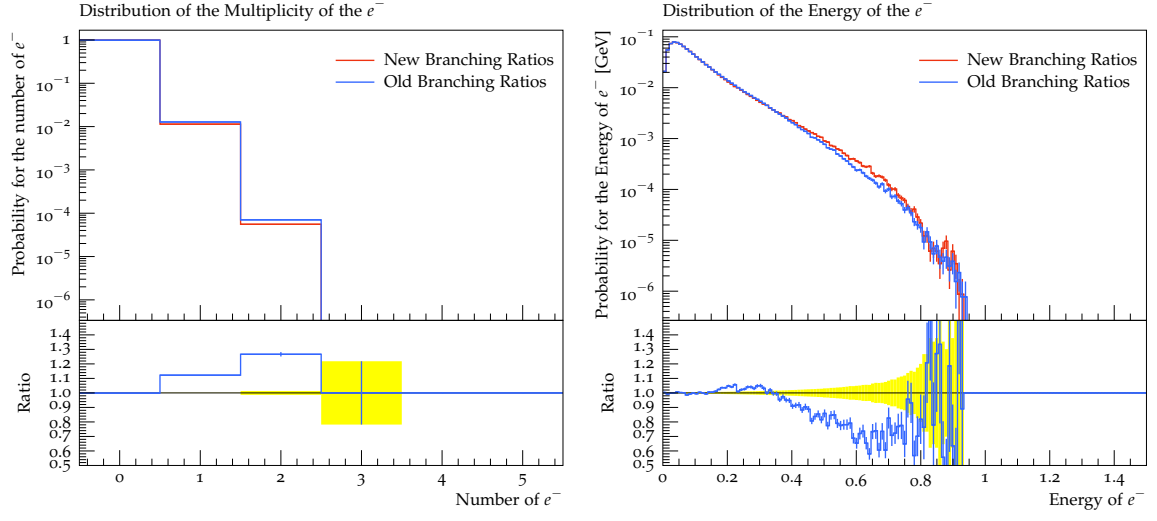


Figure A.13: multiplicity and energy spectrum of the e^-

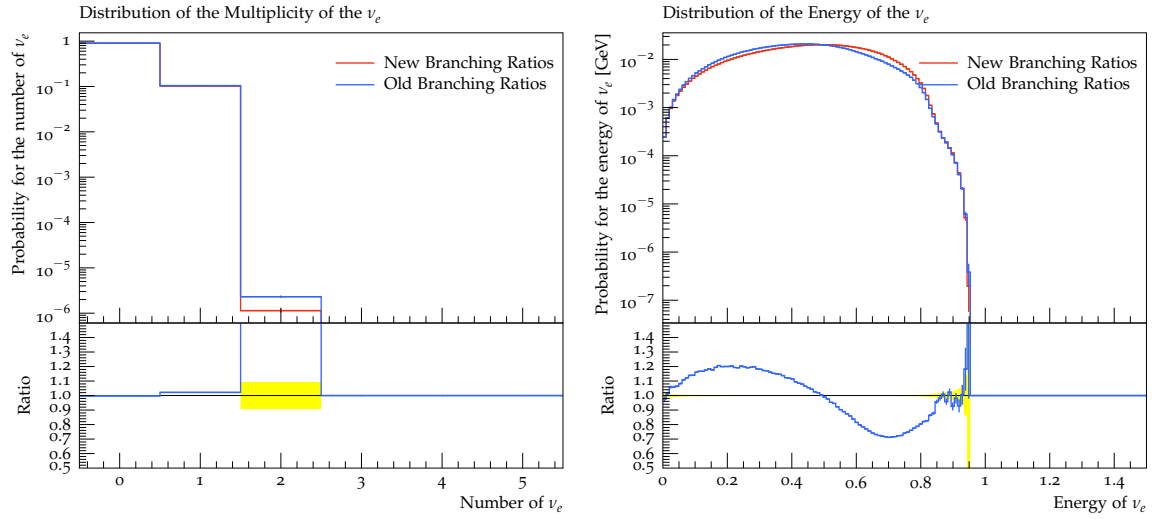


Figure A.14: multiplicity and energy spectrum of the ν_e^-

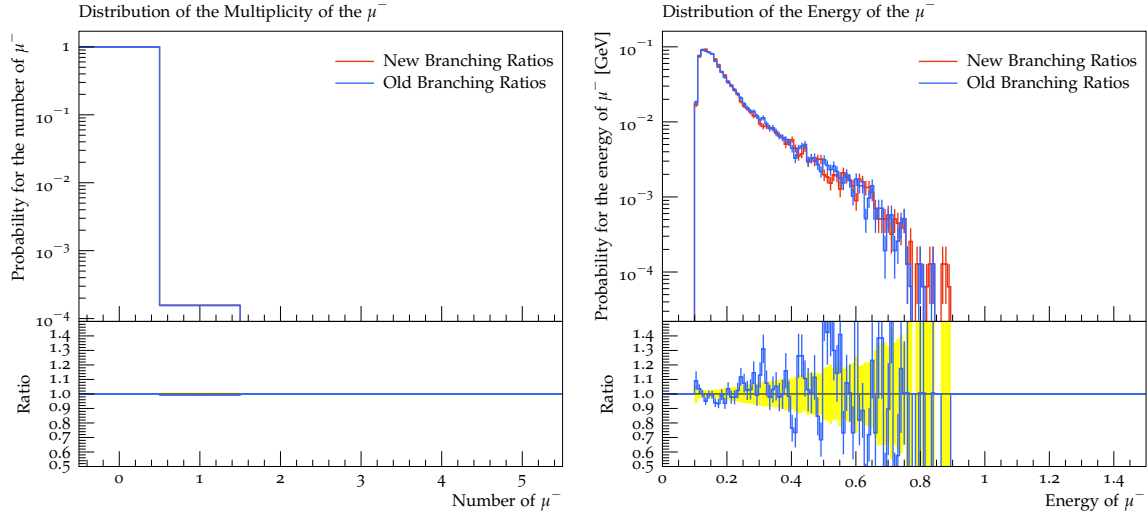


Figure A.15: multiplicity and energy spectrum of the μ^-

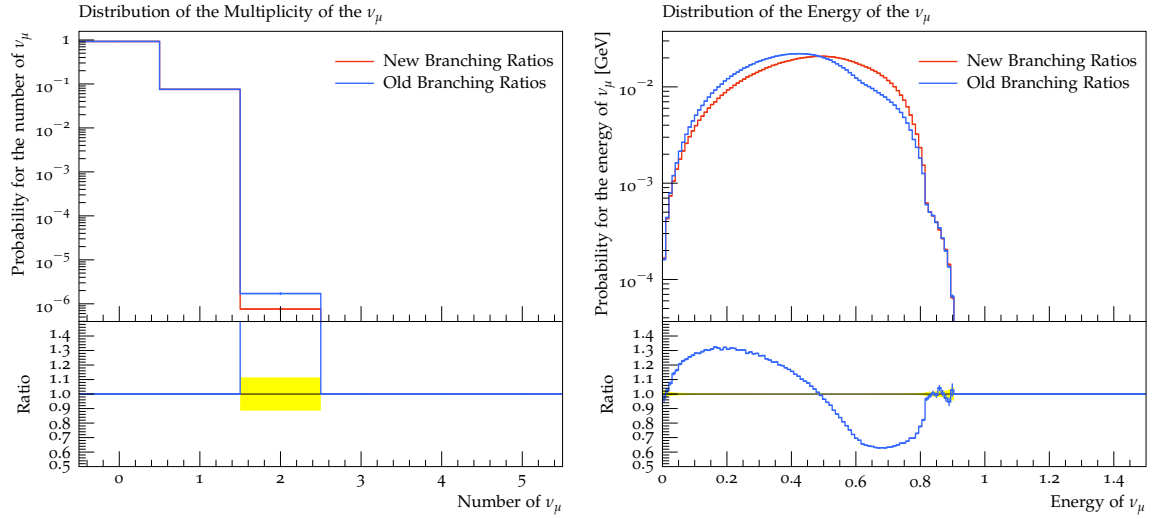


Figure A.16: multiplicity and energy spectrum of the ν_μ^-

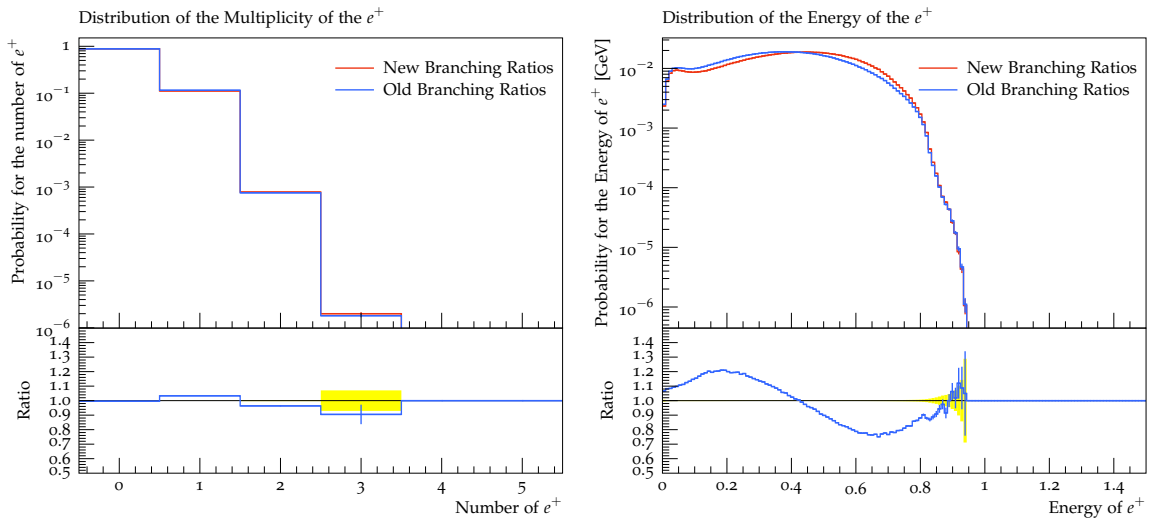


Figure A.17: multiplicity and energy spectrum of the e^+

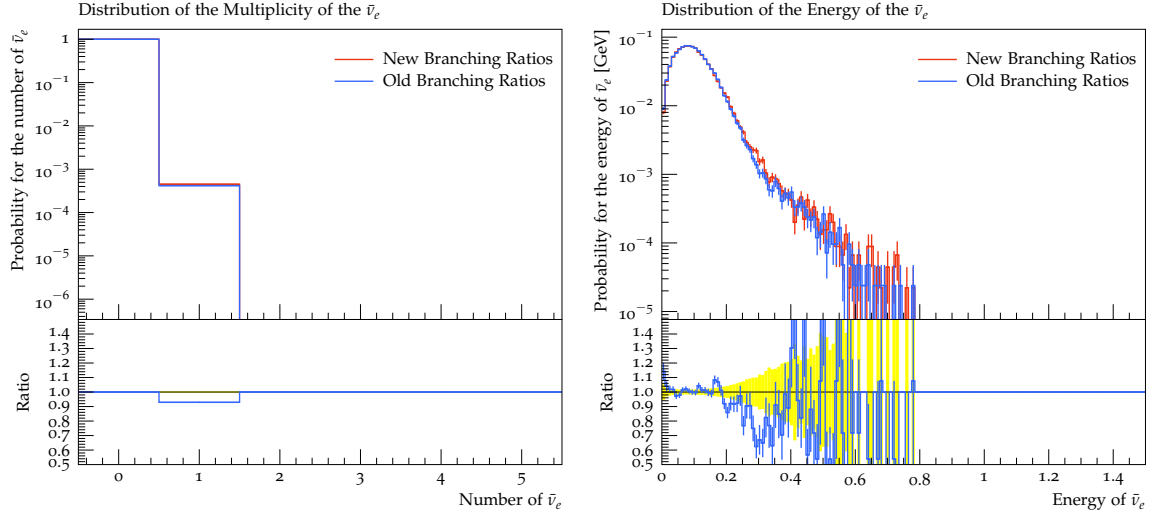


Figure A.18: multiplicity and energy spectrum of the $\bar{\nu}_e$

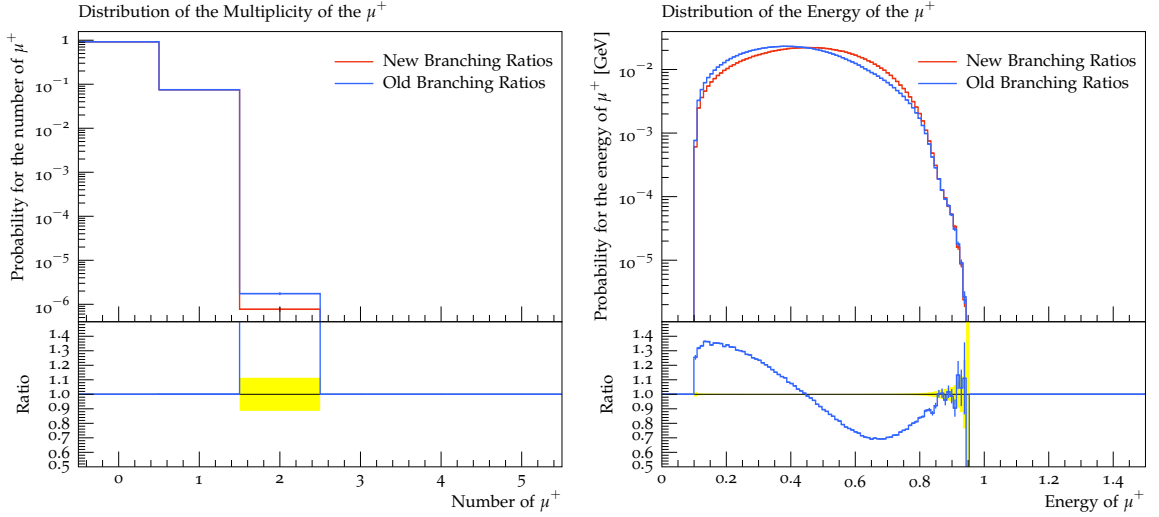


Figure A.19: multiplicity and energy spectrum of the μ^+

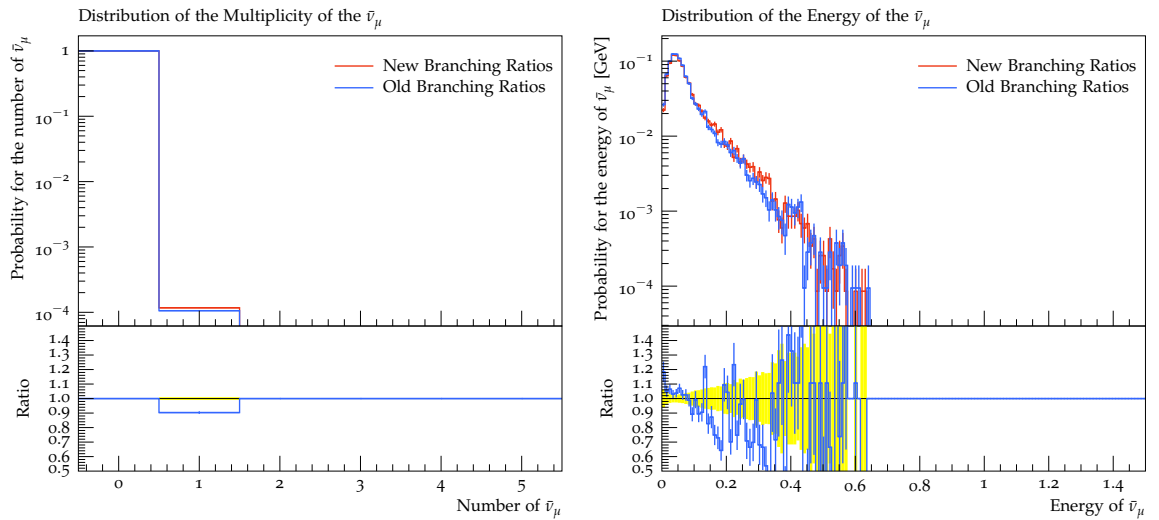
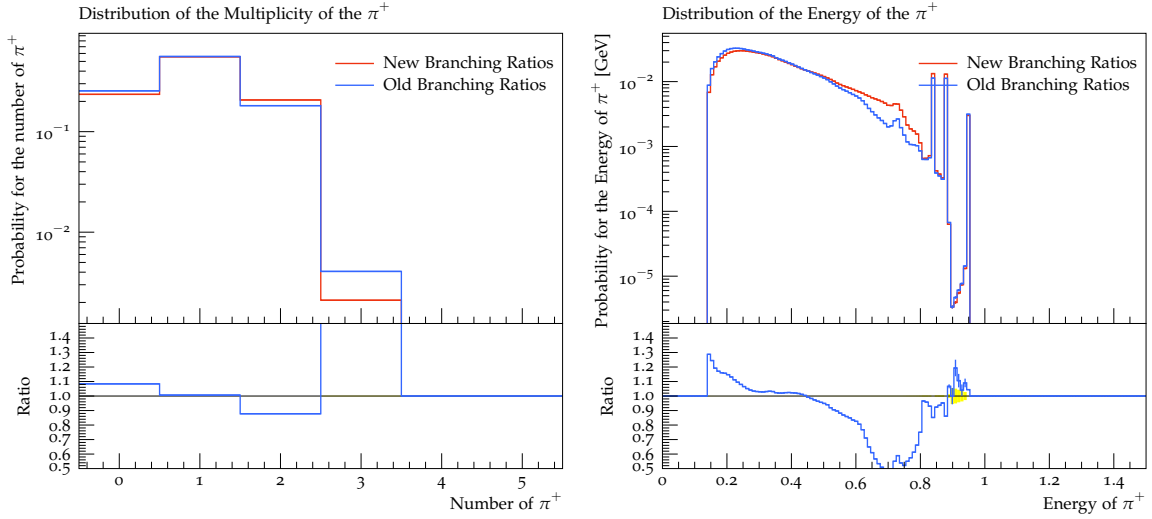
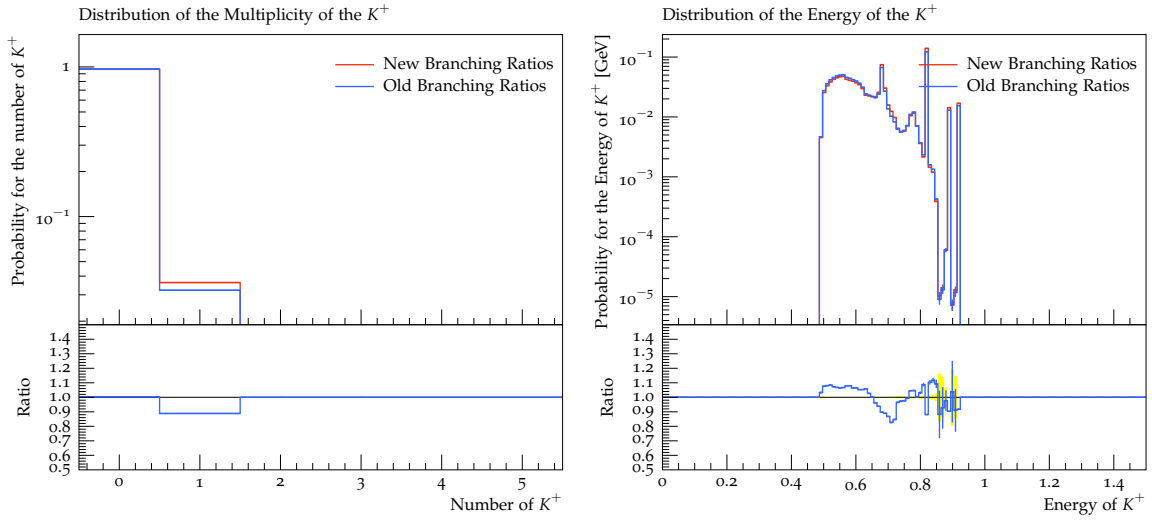
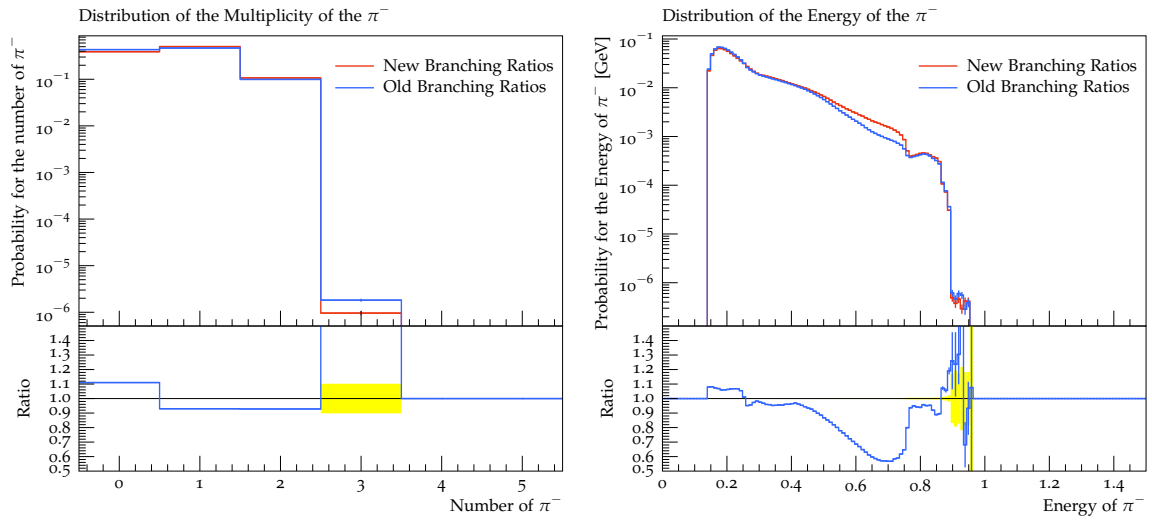


Figure A.20: multiplicity and energy spectrum of the $\bar{\nu}_\mu$

Figure A.21: multiplicity and energy spectrum of the π^+ Figure A.22: multiplicity and energy spectrum of the K^+ Figure A.23: multiplicity and energy spectrum of the π^-

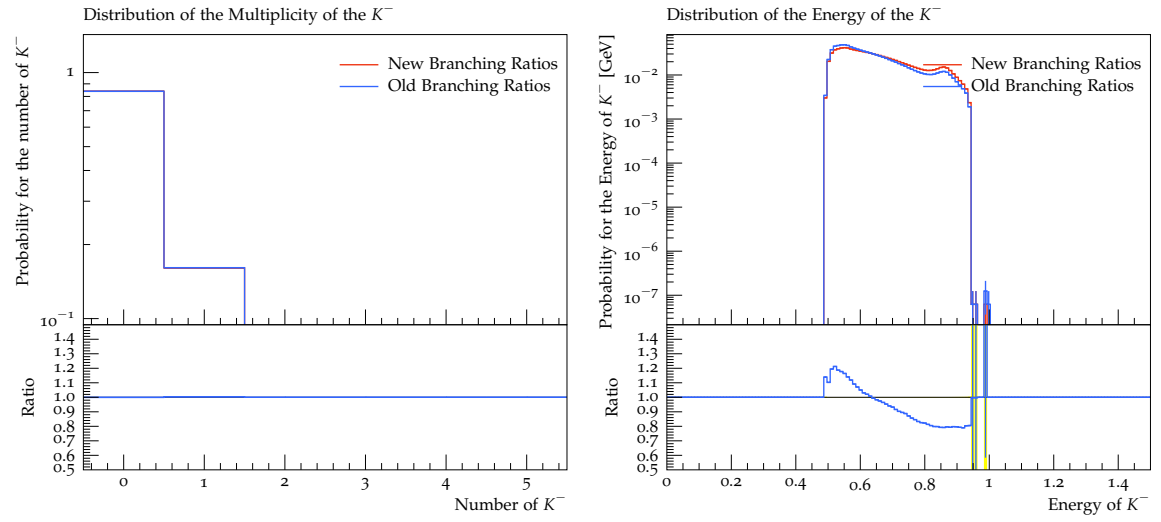


Figure A.24: multiplicity and energy spectrum of the K^-

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