Universiteit Utrecht

Natuur- en Sterrenkunde

Using collider physics to investigate high energy neutrinos

Bachelor Thesis

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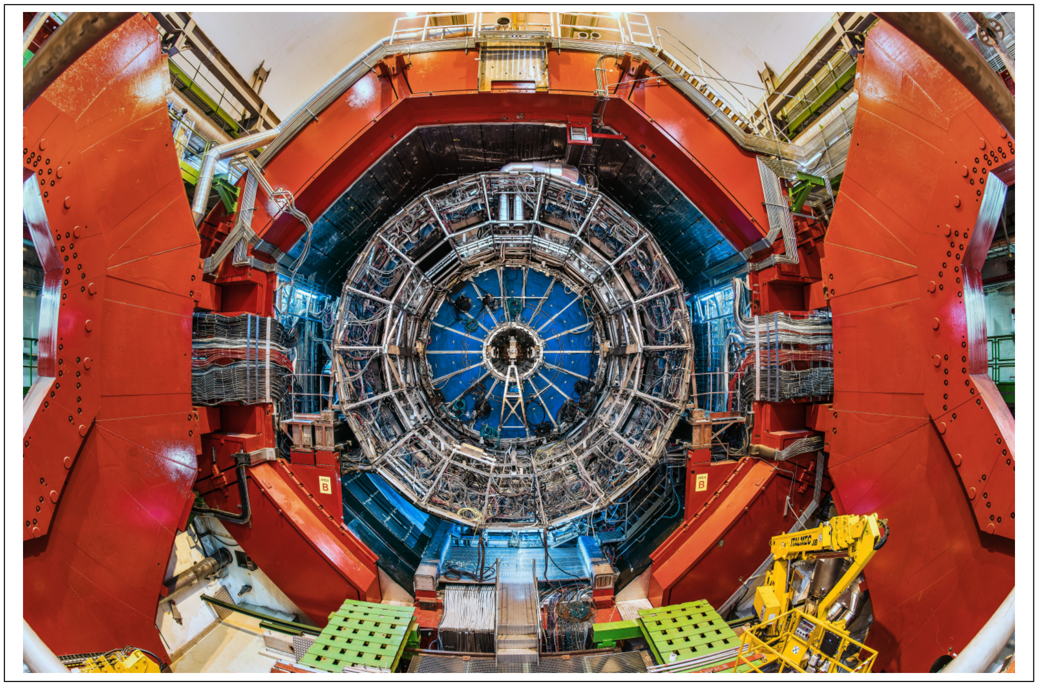

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Abstract

For a long time it was assumed that the charmed baryon-to-meson ratio was universal reflecting the universality of the charm fragmentation fractions. Due to this assumption all the event generators and MC simulations used the fragmentation fraction measured at Hera and LEP in e^+e^- collisions for all collision types and energy scales. Recently a measurement by ALICE proved that this ratio depends on the transverse momentum of the particles as well as on the collision energy [1]. The new measurements show that the ratio is a factor 4-6 higher than what was measured in e^+e^- collisions. The detailed understanding of this effect is of fundamental importance in physics. Particularly in recent years the IceCube experiment discovered the existence of astronomical neutrinos. One of the main contributors to the background signal are atmospheric neutrinos coming from charmed hadron decays in the Earths atmosphere. This background is modelled by using MC generators where the fragmentation fractions are assumed universal and set to the value measured in e^+e^- collisions. The breaking of the universality will change the neutrino flavour content and it might affect the correct representation of such a background. In this study the Pythia8 event generator is tuned such that it reproduces the Λ_c^+/D^0 ratio as measured in 7 TeV pp collisions by ALICE. Then the changes in the neutrino energy distribution are studied. The tuning is based on new colour reconnection modes made for these type of collisions. By taking the new mode that takes the full QCD colour rules into account the baryon-to-meson ratio is reproduced well. The differential production cross-section of the Λ_c^+ baryon improved between 20 and 30% while the D^0 cross-section agrees 10% less with data. There is an indication that the neutrino energy distribution changes but for the high energetic neutrinos the uncertainties are too large to be able to draw conclusions. We tried obtaining more statistics at these energies by putting a minimum momentum transfer for the parton interaction but this did not give the desired results. Hence more events must be generated and further tuning is necessary.

Frontpage image shows the ALICE detector [2].

Contents

1 Introduction

The IceCube collaboration recently showed experimental proof of the existence of Astronomical Neutrinos (AN) [3]. AN are of fundamental importance in astrophysics and cosmology as tool to investigate the cosmos. Neutrinos are weakly interacting particles without electrical charge. These properties allow them to travel straight from the point of origin for millions of years with a negligible probability to scatter or being absorbed. Therefore, neutrinos can clearly point the origin of an astronomical event. Studying their energies can give us insights on the event. The main background source for the AN are neutrinos produced in the atmosphere of our planet by charmed hadron decays (mainly D^0, D^+ and Λ_c^+). Those neutrinos mimic the energy shape and spatial distribution of the AN and therefore they can be accounted for only via monte carlo (MC) simulations. The simulations rely on experimental measurements collected at particle accelerators such as LEP. The production of D^0 mesons and Λ_c^+ baryons is simulated based on charm fragmentation fractions measured at Hera and LEP via e^+e^- collisions. For a long time this baryon-to-meson ratio was assumed universal for all p_T and it was assumed invariant for different collisions energies. Recently a study at ALICE proved that this ratio was not universal, but it depends on the transverse momenta of the Λ_c^+ and D^0 particles [1]. Furthermore they found that the Λ_c^+/D^0 ratio also differs for different collisions energies. The neutrino energy shape is expected to depend on the baryon-to-meson ratio if the energy shape of the Λ_c^+ neutrinos is different from the D^0 neutrinos. Hence using the newly discovered ratio may change the neutrino energy shape and thereby change the background shape that should be used. That would mean that the current background signal might lead to a wrong interpretation of the studied astronomical neutrino measurement. Our aim is to tune the Pythia8 event generator such that it reproduces the ALICE data. Since the Λ_c^+/D^0 ratio is calculated by dividing the differential cross-sections of the Λ_c^+ baryon and the D^0 meson it is important to compare these with ALICE data. Our goal is to tune the ratio and both the Λ_c^+ and D^0 cross-sections such that all 3 observables are reproduced as in ALICE data. Then we want to study if and in what way the neutrino energy shape changes. Furthermore it will be interesting to study the relative importance of the Λ_c^+ baryon and the D^0 meson regarding the neutrino production. Finally we want to establish if there is a need for the IceCube collaboration to include the new ALICE findings in their simulations in order to properly subtract the atmospheric neutrino background.

2 Theory

2.1 Quantum Chromo Dynamics

The theory that describes the strong interactions of the Standard Model is Quantum Chromo Dynamics (QCD). In these type of interactions gluons are the exchange particle/mediators. Unlike Quantum Electro Dynamics (QED), which has 1 mediator particle (the photon), this theory has 8 different mediator particles (gluons) which form a SU(3)-octet. In QED electrical charge is conserved while in QCD there are 3 charges that are conserved. These are called the colour charges and are by convention called red, green and blue charges. In context of strong interactions the strong coupling constant α_s is an important factor. Even though it is named a constant it does depend on the momentum transferred in an interaction. The value of α_s was determined by various institutes such as the ALPHA collaboration [4]. For low momentum transfer the coupling is large while for high momentum transfer the coupling is small. Hence hard interactions can be described by perturbative calculations while softer interactions cannot. The first property of QCD is asymptotic freedom. Quarks behave like free particles at distances smaller than a nucleus. Since the interaction at low energies is so strong colour charges, which are either quarks or gluons, cannot exist separately. Hence they must always form hadrons. This is the second important property of QCD and it is called colour confinement and it directly follows from the asymptotic freedom. QCD is described by the Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} + \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j \tag{1}$$

where $G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu$ is the kinematic field tensor. When quarks bind they form hadrons. A hadron that consist of 2 quarks is a meson and a hadron that consist of 3 quarks is a baryon. Mesons have integer spin and are therefore bosons, baryons have half integer spin and are therefore fermions. Mesons consists of a quark and an anti-quark while baryons can consist of 3 quarks, anti-quarks or a mixture of both. Charmed mesons are produced asymmetrically because of $c\bar{c}$ production where there is a preferential recombination between $\bar{c}$ quarks with valence d quarks. Before hadronizing a heavy quark binds with a lighter parton. This quark recombination model allows perturbative and non-perturbative calculation up to higher orders.

2.2 Heavy baryon-to-meson ratio and neutrino energies

Examples of charmed baryons and mesons are the Λ_c^+ baryon and the D^0 meson. These particles have very short lifetimes. During their decays leptons may be produced as well as hadrons. In such a case we refer to semileptonic decays. As discussed in the introduction, these hadrons are also formed in atmospheric hadron-hadron collisions when a high energetic cosmic ray from outer space collides with a particle in the atmosphere. Because the initial colliding particles travel along the radial direction of the atmosphere the decay product do also have very forward pseudorapidities. That means that the almost travel along the original collision direction. Due to momentum conservation the differential cross-section of the hadrons determines the differential cross-sections spectra of the decay particles. Since the baryons and mesons coming from those collisions have momenta in the GeV/c scale and neutrino rest masses much smaller than 1 GeV/c^2 the momenta of the neutrinos is the dominant factor in the neutrino energies as well. The differential cross-section is related to the momentum spectra via

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{2c_{\Delta y}} \frac{1}{BR} \frac{f_{prompt} N_{|y|<y_{fid}}}{(A \times \epsilon)_{prompt}} \frac{1}{\mathcal{L}_{int}} \tag{2}$$

where $\frac{f_{prompt} N_{|y|<y_{fid}}}{(A \times \epsilon)_{prompt}} = dN/dp_T$ and $\mathcal{L}_{int}$ is the number of events [1]. The energy spectra of the neutrinos hence follows from the momentum spectra of the mother particles. Note that in this thesis all decay channels are taken into account such that BR = 1. The Λ_c^+/D^0 ratio was carefully determined in electron-electron collisions by LEP, ARGUS and CLEO [1]. The ratio varies between 0.113 and 0.127 depending on the reference and is the same for all p_T. Recently it was found by ALICE that this ratio was different in high energetic pp and p-Pb collisions which could affect the neutrino energy shape as stated in the introduction [1].

2.3 Large Hadron Collider and the ALICE collaboration

The LHC is the largest particle accelerator in the world with a circumference of 27 km. Particles such as protons or Pb nuclei are accelerated to velocities up to almost the speed of light. The collision energies lay between 5 and 13 TeV. One of the detectors at the LHC is built by the ALICE collaboration. At ALICE they aim to study the Quark Gluon Plasma which is a state of matter where quarks and gluons are deconfined in a plasma-like substance. Their enormous detector consist of various detector components where each has its own capacities. An illustration is shown in Figure 1.

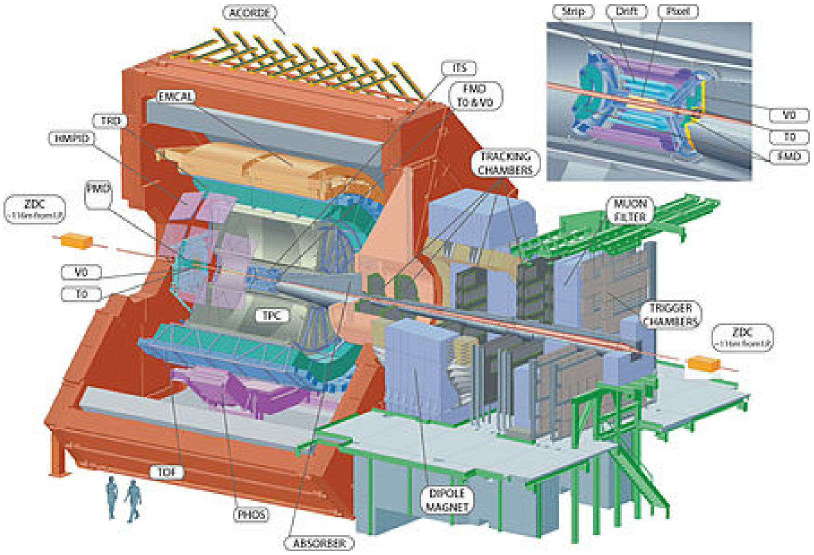

Figure 1: Illustration of the ALICE detector with all the components marked. Every component is explained in the text. Illustration from [5].

Identifying particles is complex and a combination of detector traces is required to be able to identify a certain particle. Even though the the detector is 'small' compared to other detectors at the LHC it still weighs 10.000 tons [5]. The detector predominantly looks in the transverse direction between $|\eta| < 0.9$. Where η is the pseudorapidity of a particle which is defined as $\eta = -\ln[tan(\frac{\Theta}{2})]$. The central part of the detector consist of detectors that measure hadrons, electrons and photons. This is done by combining Silicon Trackers, Time Projection Chambers, Particle identificators and Calorimeters. The silicon trackers detect (only) charged particles. When a charged particle is placed in a magnetic field it will bend due to the Lorentz force. The silicon trackers measure the x and y coordinates of the particles. There are 3 types of silicon detectors, the Silicon Pixel Detector (SPD), the Silicon Drift Detector (SDD) and the Silicon Strip Detector (SSD). After the silicon detectors there is a Time Projection Chamber. In this detector particles leave an ionization trace. The electrons drift towards electrodes and from that the spatial coordinates of the particle can be determined. The first particle identification detector is the Time Projection Chamber (TPC) which measures the energy loss over a certain distance, dE/dx. The second particle identification detector is the Time of Flight (TOF) System. It meanly distinguishes between pions, kaons and protons. The detector measures how long it takes for particles to pass to the detector and hence it is capable of determining a particles velocity. Then particles move trough the High Momentum Particle Identifier (HMPID). This detector uses the angle between emitted Cherenkov radiation and the particle track to determine a particles velocity. Cherenkov radiation is emitted when a particle moves faster than the speed of light in that medium. When the momentum and a velocity of a particle is known the mass can be deduced which is of course characteristic for a certain particle. Surrounding the TPCs there are 18 Transition Radiation Detectors. Transition radiation is emitted when a particle moves from one medium to another. This detector mainly distinguishes between rare particles (i.e. electrons) and more conventional particles (i.e. pions). Now a particles position and velocity are well determined but a particles energy hasn't yet be determined. In order to do this ALICE uses various types of calorimeters. In a calorimeter a particles deposits (most of) its energy. Hence this is a destructive measurement. The electromagnetic calorimeter is called PHOS and is capable of detecting photons, neutral mesons and electrons/positrons. Generally hadrons are often detected in a hadronic calorimeter. They do leave a trace in electromagnetic calorimeters but they do not deposit all their energy there. Muons leave traces in most detectors but in the previously mentioned calorimeters they do not deposit all their energy. To be able to detect muons a muon spectrometer is used. A lot of layers are required to be able to detect the muons. Furthermore a hadron absorber is placed at the front of the spectrometer to prevent disturbance by hadrons. The only particles that are not detectors are neutrinos since they do not feel any type of interactions. Neutrino detectors are often much larger than the ALICE detectors (such as the IceCube detector). The combination of the signal in the tracking devices, TOF detectors and the calorimeters reveals a particles identity.

2.4 IceCube neutrino observatory

The IceCube neutrino observatory aims to study cosmic neutrinos. With these studies they want to learn more about the properties of the neutrinos themselves and the nature of dark matter. Furthermore the neutrinos could provide information about the most violent events in the cosmos such as exploding stars and gamma ray bursts. For very high energetic photons the universe is opaque when travelling very large distances while for neutrinos with the same energy the universe is still transparent. Hence neutrinos can be used to study regions further away from Earth. An illustration is shown in figure 2.

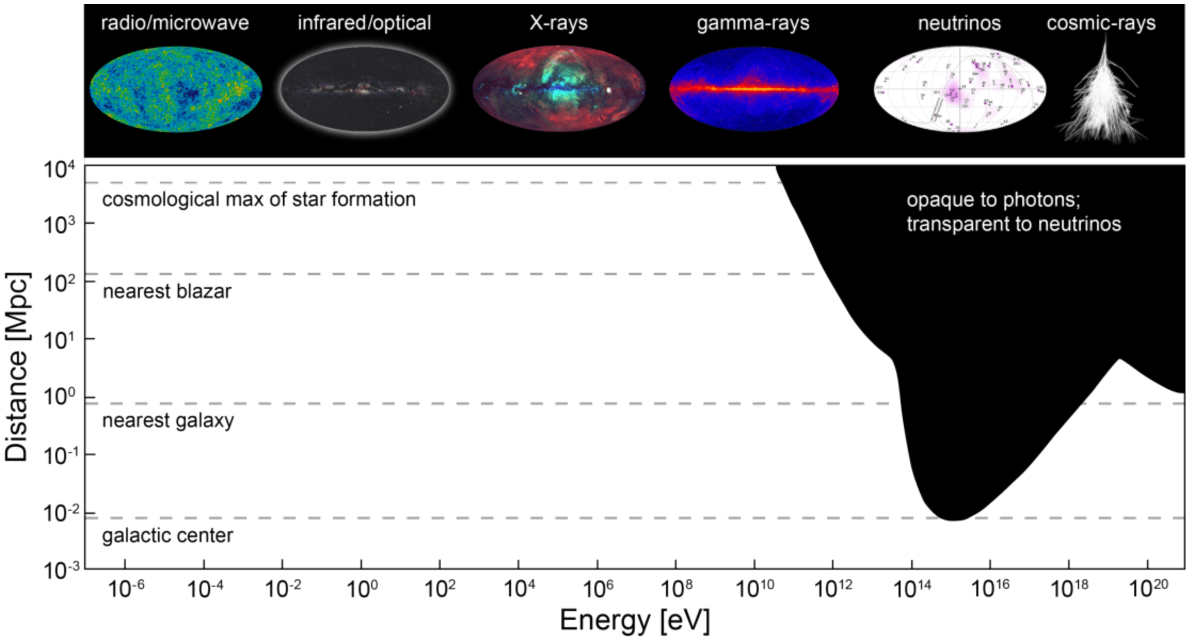

Figure 2: Distance a photon can travel as function of its energy before the universe becomes too opaque [3].

In addition, IceCube aims to study dark matter by looking at neutrino's coming from dark matter annihilation. IceCube also contributed in research on glaciology by looking at the ice layers at the bottom of the detector. The detector is the first one if its kind. It is built in a block of ice with a size of 1 km^3 and it reaches depths up till 2500 m below the surface [3]. The detector consist of more than 5000 Digital Optical Modules (DOMs) and 86 boreholes which are all laying 125 m apart. In each borehole a string is placed with 60 DOMs attached. Vertically the string has 1 DOM every 17 meters. The center of the detector is a bit more densely constructed. Here 8 strings are only 70 meter apart and vertically every 8 meter a DOM is placed. This denser part of the detector forms the DeepCore subdetector and it has a neutrino energy threshold of 10 GeV, low enough to study neutrino oscillations. An illustration of IceCube can be found in figure 3.

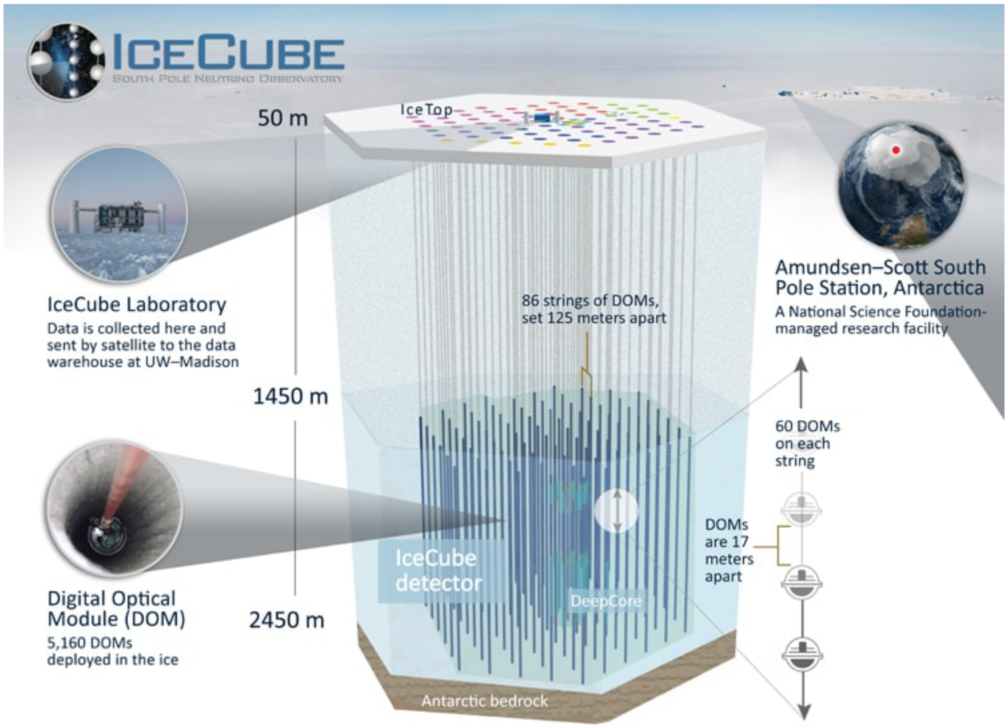

Figure 3: The IceCube detector [3].

3 Experimental Setup

3.1 PYTHIA 8

Since IceCube uses generators tuned on e^+e^- measurements to determine their background signal it is interesting to study if the breaking of the universality of the charm fragmentation fraction measured by ALICE for collisions at the TeV scale has consequences for the neutrino energy shape. For this study we perform a tuning on the Pythia8 MC event generator to reproduce the baryon-to-meson ratio. The Pythia8 event generator is widely used under particle physicists and different collaborations such as ATLAS, ALICE, CMS and many others. It can simulate high energetic collisions between different species of nucleons and nuclei such as proton-proton (pp) or proton-lead (p-Pb). Our standard version of Pythia8 will make usage of the 2013 Monash Tune by P. Skands, which reproduces the main of observables at the TeV scale very well as seen in [6]. In this study we solely investigate pp collisions at 7 TeV in order to tune the simulation against the charm baryon-to-meson ratio measured by ALICE at the same energy. Pythia8 uses both perturbative and parametrizations of non-perturbative physics to reproduce the collisions physics. Using this starting point as a baseline we aim to tune Pythia8 such that it reproduces the ALICE data from the Λ_c^+/D^0 ratio as well as both the differential cross-sections. Once this is achieved we aim to use Pythia8 to investigate the possible change of the neutrino energy shape at forward rapidity $\eta > 5$.

3.2 Lund String Fragmentation Model

The Lund String Fragmentation Model describes how new particles form after a hadron collision. This model is also used in the Pythia8 event generator for both light and heavy flavour quark string fragmentation. As stated before one of the properties of QCD is confinement, which means quarks cannot exist separately. For large charge separation the quantum field lines seem to be compressed in tubelike regions [7]. These compressed field lines form strings, which do not have transverse excitations. String fragmentation models are probabilistic and iterative in general [8]. Hence the string fragmentation as a whole is the sum of underlying branching fractions. A branching fraction is for example $String \to Hadron + Remainderstring$. The basic idea of string fragmentation is as following. A string forms between a $q\bar{q}$ pair. Since the quarks separate from each other due to their opposite momenta the string energy, which is proportional to its length, increases. This allows the string to break and form a new $q\bar{q}$ in the middle [8]. The result is that we now have 2 strings and 2 pairs. This process repeats until On-mass-shell (real) hadrons are produced. In the Lund model the p_T spectra of the pairs are Gaussian. Since strings themselves do not have transverse excitations the p_T is locally compensated by the $q\bar{q}$ pairs [8]. The light flavour string breaks are governed by the following relation

$$f(z) \propto \frac{1}{z}(1-z)^a exp(-bm_\perp^2/z) \tag{3}$$

where $m_\perp = m_{Hadron}^2 + p_{\perp,Hadron}^2$ and z is the energy of the formed hadron due to the string break. Here a en b are constants which have to be determined experimentally [7],[6]. Directly via the relation we can see that hard regions are suppressed when the value of a is large and that soft regions are suppressed when the value of b is large. Both these values can be changed in Pythia8 by changing StringFlav:aLund and StringFlav:bLund. For heavy flavour quarks the string function is $f(z, m_Q) = \frac{f(z)}{z^{br_Q m_Q^2}}$, where b is the same parameter is before, m_Q is the quark mass and r_Q is a constant that has to be determined numerically. For the charm quark $r_c = 1.32$ [6].

3.3 Colour Reconnection Modes in Pythia8

Colour reconnection is a mechanism in which final state partons are connected by a colour string. These strings follow the movement of the partonic end points. This movement results in a boost of the string fragments. The mechanism is used to explain problems that arised by describing the expansion of the QGP by hydrodynamic flow [9].

Pythia8 has three different CR modes for pp collisions. Each mode is based on different fundamentals.

The default mode, mode 0, is based on string length minimization. Partons are classified as low or high p_T systems. Then Pythia connects a low p_T system with a high p_T such that the string length/energy is minimized. There is a certain probability that systems can merge [10].

$$P = \frac{P_{T-Rec}^2}{P_{T-Rec}^2 + P_T^2} \tag{4}$$

Hence low p_T can merge with any system while merging high p_T systems is less probable. The only tunable parameter for this mode is ColourReconnenction:Range, which allows more reconnections if the value is higher.

The mode based on the newer scheme, mode 1, is also based on the minimization of string length but does it in a different way. This mode also takes colour rules from QCD into account. The main feature of this model is that it allows for junction structures between strings. The model reconstructs all colour dipoles that are allowed by QCD rules and replaces a dipole with another if it results in a lower string length. This process is repeated until Pythia cannot find a dipole that minimized the string energy further. Each dipole gets a number between 0 and 8, only dipoles with the same number are allowed to reconnect. This is added to the CR mode in order to allow the creation of a colour singlet coming from an uncorrelated triplet and anti-triplet every 1/9 times [10]. Because of this repetitive origin it takes more time to run a model with this CR mode.
This mode should be combined with BeamRemnants:remnantMode=1 [10]. Furthermore it is recommended to start with MultipartonInteractions:pT0Ref = 2.15 and ColourReconnection:allowDoubleJunRem = off. It is also stated that parameters outside the CR section need to be tuned in order match data well. This will be discussed in further detail in section 3.4. This mode has 9 different parameter options. For a full list see [10]. The most important ones are ColourReconnection:m0 and ColourReconnection:junctionCorrection. The first

parameter is used a reference mass that is used in the measurement of string lengths. The latter is a reference mass that is only used in string junction calculations.

The last mode that can be used for pp collisions is mode 2. This colour reconnection mode is based on moving gluons and then flipping the positions of two connected gluons. First all final state gluons and colour-reconnected parton pairs are identified. For each parton pair it is calculated what the string length would be if a gluon was placed between the partons. The gluon move that minimized the string length is carried out. There is a limit on how much minimization can occur by executing a single move. The gluon movement does not break the connection between string endpoints. Only number of gluons between the endpoints may change. Furthermore there is an option to flip the position of the gluons between the strings endpoints. This is only done if the string energy minimizes. Only one flip may take place and a string is not allowed to flip with itself.
The most important parameters are ColourReconnection:fracGluon, ColourReconnection:dLambdaCut and ColourReconnection:m2Lambda. The first one determining the probability that a gluon is considered movable. The second parameter sets the limit for minimization per single move. The third parameter is a reference mass for string length minimization. It has a similar role as ColourReconnection:m0 in CR mode 1.

3.4 Structure of the MC Simulations

For this study the STOOMBOOT computer cluster at Nikhef was used. This cluster consist of 32 dual quad-core processors which means that it has 256 cores in total. For each run a minimum of 500 million events is generated to provide us with significant statistics at the observed energy and transverse momentum scales. The collision energy is fixed at 7 TeV for every simulation. After the collision Λ_c^+ and D^0 particles are selected. If their pseudorapidity $\eta < 0.9$ the particles transverse momentum is added to a histogram. From these dN/dp_T histograms the differential cross-sections can be obtained by using Equation 2. Since all the Λ_c^+ and D^0 particles are selected the branching ratio $BR = 1$. The $\eta < 0.9$ cut is chosen such that it matches with the detection range of the ALICE detector, which predominantly detects particles at central rapidities [5]. After this procedure the decay channels of the selected hadrons are analysed. Since semileptonic decays of these hadrons always result in the production of at least 2 leptons and another particle the minimum amount of decay products was chosen 3. Because the fully hadronic decay modes are skipped the simulations runs faster. If one of the decay products is a neutrino its energy is added to a histogram provided that its pseudorapidity $\eta > 5$. This η cut is chosen because the neutrinos coming from atmospheric hadron collisions travel at very forward rapidities. Each hadron has its own set of 3 energy histograms, one for each flavour. In a separate code the cross-sections are divided to obtain the Λ_c^+/D^0 ratio.

4 Results

The tunes in this study are based on the newer Colour Reconnection Modes in Pythia8. The first set of tunes is based on CR mode 1 and the second set of tunes is based on CR mode 2. The tuning in both sets is done in roughly the same way. First both modes are studied with their default values. After that the Lund Parameters are modified while the settings for the CR modes remain the same. At the same time the baryon production is enhanced by decreasing StringFlav:probQQtoQ, which allows for more diquarks than single quarks when the value is lower. Strange quark production is enhanced by lowering StringFlav:probStoUD. Spin 1 diquarks are suppressed by StringFlav:probQQ1toQQ0join. Finally CR mode 1 is further optimized by changing the reference mass and the junction reference mass.

4.1 The Monash Tune

First we simulated 2×10^9 collisions at 7 TeV in the standard version of Pythia8. The baryon-to-meson ratio has values between 0.05 and 0.09 and increases slightly for higher p_T which is identical to the ratio of the Monash Tune in Figure 11 of [1]. The fact that we can reproduce the published result gives us confidence that we are able to properly handle the code. The differential cross-sections do not agree with data as can be seen in Figure 5. The cross-section of the Λ_c^+ baryon is very poorly reproduced with MC/Data values between 0.01 and 0.15 depending on the transverse momentum. Even though the D^0 cross-section does not fully agree with data it is between 5 and 10 times better than the differential cross-section of the Λ_c^+ baryon with the largest differences occurring at low transverse momentum. At intermediate p_T values the MC/Data ratio for the cross-sections is around 0.65 for the D^0 meson while for the Λ_c it is around 0.1. The results from the Monash Tune will be used as a reference to compare the additional tuning performed in this thesis.

4.2 Colour Reconnection Mode 1

This set of tunes is based on ColourReconnection:mode=1. First only ColourReconnection:mode=1 was enabled. As suggested by the manual we combined this colour reconnection mode with BeamRemnants:mode=1 [10]. A beamremnant mode finishes the process of adding primordial k_T to initiators and remnants by assigning the relative longitudinal momentum sharing among the remnants. Furthermore it regulates the colour flow along the remnants. The CR mode parameters remained default. This mode will be referred to as PYTHIA 8 CR1 in figures and tables. For this run 2×10^9 events were generated at 7 TeV. As seen in Figure 4 the baryon-to-meson ratio agrees more with data, with values ranging between 0.2 and 0.3. The ratio is decreasing a function of p_T which is also the trend the data follows. The differential cross-section of the Λ_c^+ improves almost 10% for all p_T. The differential cross-section of the D^0 meson agrees less with data by 5 to 15% with larger differences for small p_T. On the left side of Figure 6 it can be seen that the shape of the neutrino energy distribution at forward rapidity does not change drastically but when the ratio is taken differences between 1 and 4% can be seen at energies below 400 GeV. At higher energies the ratio becomes larger than 1. Differences larger than 10% can be observed, but the uncertainties become too large after 600 GeV to be able to draw rigorous conclusions. In

Figure 7 we see that the neutrinos coming from decaying Λ_c^+ baryons are much more relevant at energies below 500 GeV. At energies below 200 GeV the ratio changes from values close to 0.06 to values close to 0.2.

The next step that was made to reproduce the data even better was the modification of the Lund parameters and the quark decay probabilities discussed at the beginning of the results section. This was suggested by [11]. In this tune the CR mode parameters were still the default values. The StringZ:aLund parameter was changed from 0.68 to 0.36 and the StringZ:bLund parameter was changed from 0.98 to 0.56. An overview of all the parameters can be seen in Table 1. Again 2×10^9 events were generated at 7 TeV. For this tune we can see that the baryon-to-meson ratio agrees with data at transverse momenta between 1 and 3 GeV/c but note that the data points lay at the edges of the data uncertainties. For higher transverse momenta the ratio is approximately 0.1 lower than data. The simulated ratio decreases faster as a function of p_T than the data as can be seen in Figure 4. The differential cross-section of the Λ_c^+ baryon improves by 0.2 compared to the Monash Tune. However the differential cross-section from the D^0 meson agrees 0.2 less with data compared to the Monash Tune. The total neutrino energy distribution changes again, but the ratio seems to have a different shape compared to the previous tune at energies above 600 GeV. This may be due to the large uncertainties at those energies. At energies up to 200 GeV a clear difference of 5% can be seen between the this tune and the previous one. Hence the neutrino energy shape is changed more by this tune than by the previous tune (CR1). In Figure 7 we see that the neutrinos coming from Λ_c^+ decays become even more important. The difference is around 10% for energies up to 500 GeV. For energies higher than 500 GeV the ratio seems to agree with the CR1 tune and at energies above 2 TeV the uncertainties of this tune (CR1 Tune 1) and the Monash Tune overlap. It would be interesting to see if this ratio really agrees with the Monash Tune but to be able to see that much more statistics are required.

The final tuning of ColourReconnection:mode=1 was done by changing the parameters connected to the CR mode itself. For this tune (CR1 Tune 2) 2×10^9 events were generated at 7 TeV. The parameter changes were suggested by [12]. Again the modified Lund parameters and quark decay probabilities of CR1 Tune 1 were used. All parameter settings can be found in Table 1. The Λ_c^+/D^0 ratio agrees with data between 3 and 8 GeV/c. Between 1 and 3 GeV the data is very slightly overshot with the points laying slightly above the upper uncertainty limit of the ALICE data. Since the statistics is large in the simulation for the low momenta regions the errorbars of the simulation are very small and hence they do not overlap. The Λ_c^+ cross-section improves between 0.2 and 0.3 compared to the Monash Tune and between 0.4 and 0.8 compared to CR1 Tune 1. The agreement of the D^0 cross-section with data decreases between 0.02 and 0.12 compared to the Monash Tune, which is less than the increase observed in the baryon cross-section. This was to be expected since the ratio largely improved. The neutrino energy distribution changes up to 13% at energies below 500 GeV with the peak occurring at 40 GeV. Due to high uncertainties it is hard to determine how the energy distribution is affected at energies above 500 GeV.

Parameter	**Monash**	**CR1**	**CR1 Tune 1**	**CR1 Tune 2**
ColourReconnection:mode	0	1	1	1
StringPT:sigma	0.335	0.335	0.335	0.335
SringZ:aLund	0.68	0.68	0.36	0.36
StringZ:bLund	0.98	0.98	0.56	0.56
StringFlav:probQQtoQ	0.081	0.081	0.078	0.078
StringFlav:probStoUD	0.217	0.217	0.2	0.2
StringFlav:probQQ1toQQ0join	0.5, 0.7 0.9, 1.0	0.0275 (4x)	0.0275 (4x)	0.0275 (4x)
MultiPartonInteractions:pT0Ref	2.28	2.28	2.15	2.15
ColourReconnection:m0	-	0.3	0.3	2.17
ColourReconnection:junctionCorrection	-	1.20	1.20	9.33
ColourReconnection:timeDilationMode	-	2	2	2
ColourReconnection:timeDilationPar	-	0.18	0.18	0.18
BeamRemnants:remnantMode	-	1	1	1
BeamRemnants:saturation	-	5	5	5

Table 1: Parameter settings for the tunes based on ColourReconnnection:mode=1.

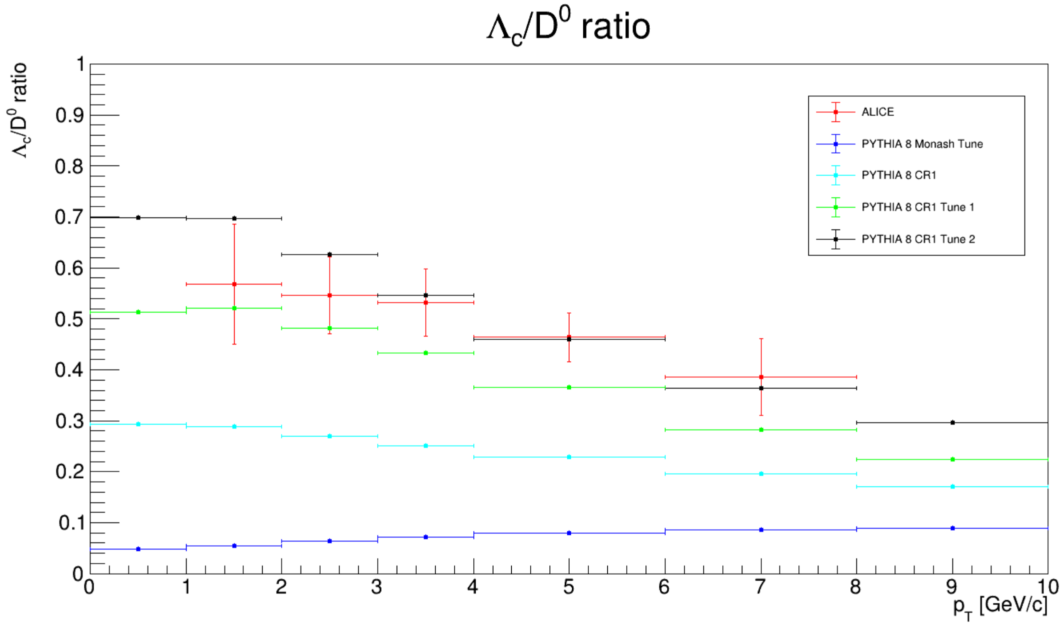

Figure 4: The Λ_c^+/D^0 ratio as a function of transverse momentum (p_T) for different simulations compared to ALICE data [1]. The Monash Tune is the standard version of PYTHIA 8. PYTHIA 8 CR1 is with solely CR mode 1, PYTHIA 8 CR1 Tune 1 is the tune with different Lund parameters and PYTHIA 8 CR1 Tune 2 has different CR mode parameters.

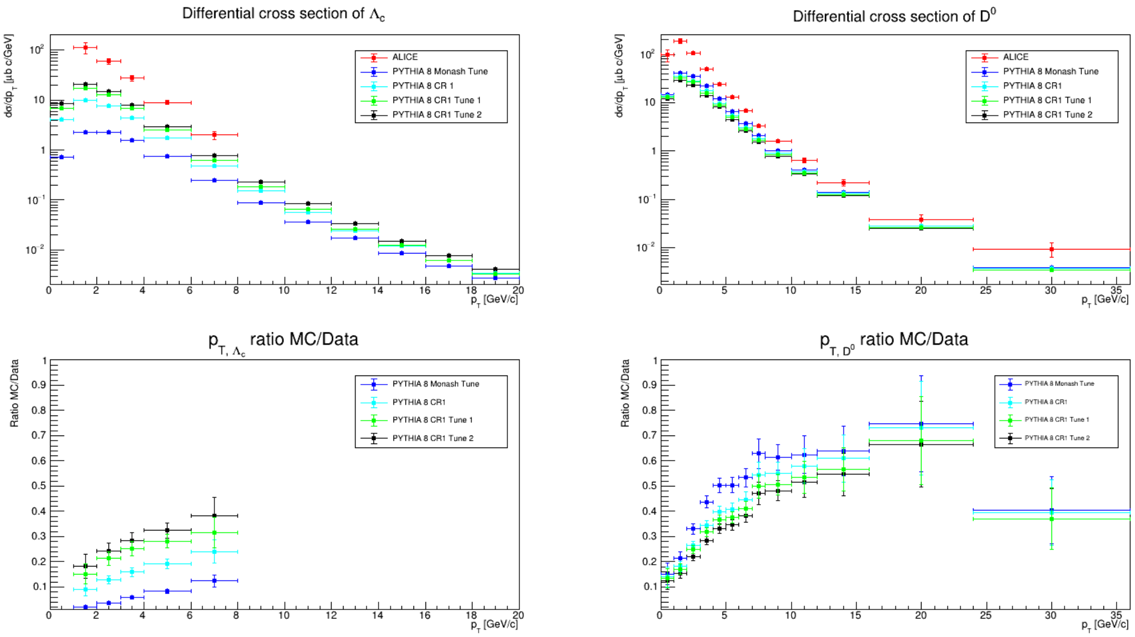

Figure 5: Upper: Differential cross-section for Λ_c^+ baryons and D^0 mesons at central rapidity $\eta < 0.9$ compared to ALICE data [13], [1]. Lower: Ratio MC/Data.

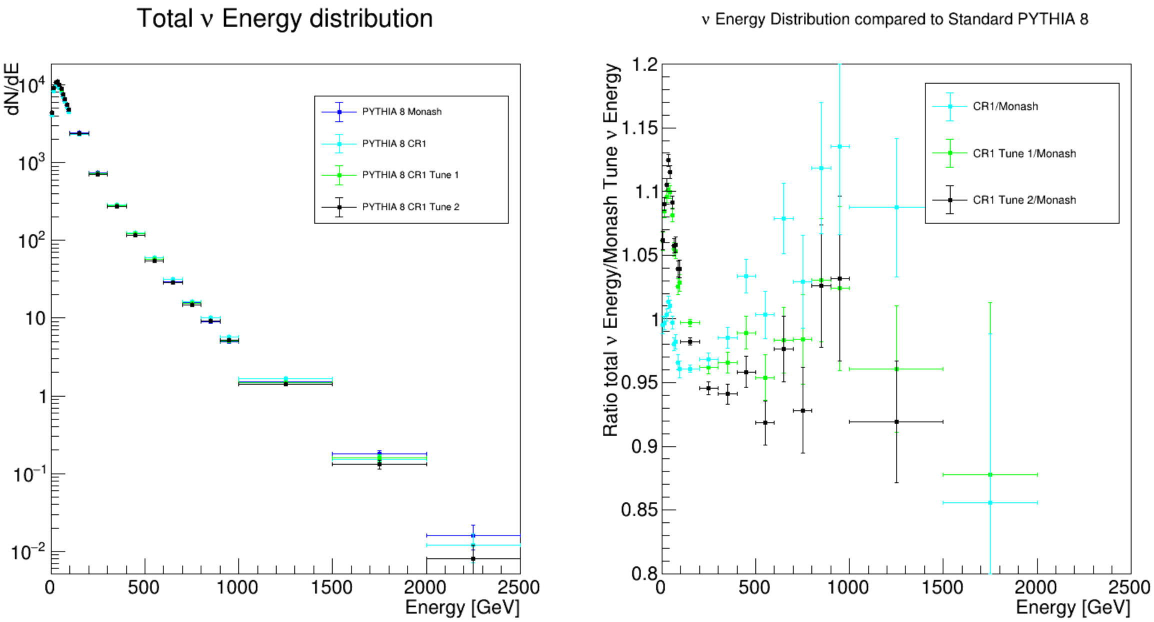

Figure 6: Left: Total energy distribution of both Λ_c^+ and D^0 daughter neutrinos at forward rapidity $\eta > 5$. Right: Ratio compared to Monash Tune neutrino energy distribution.

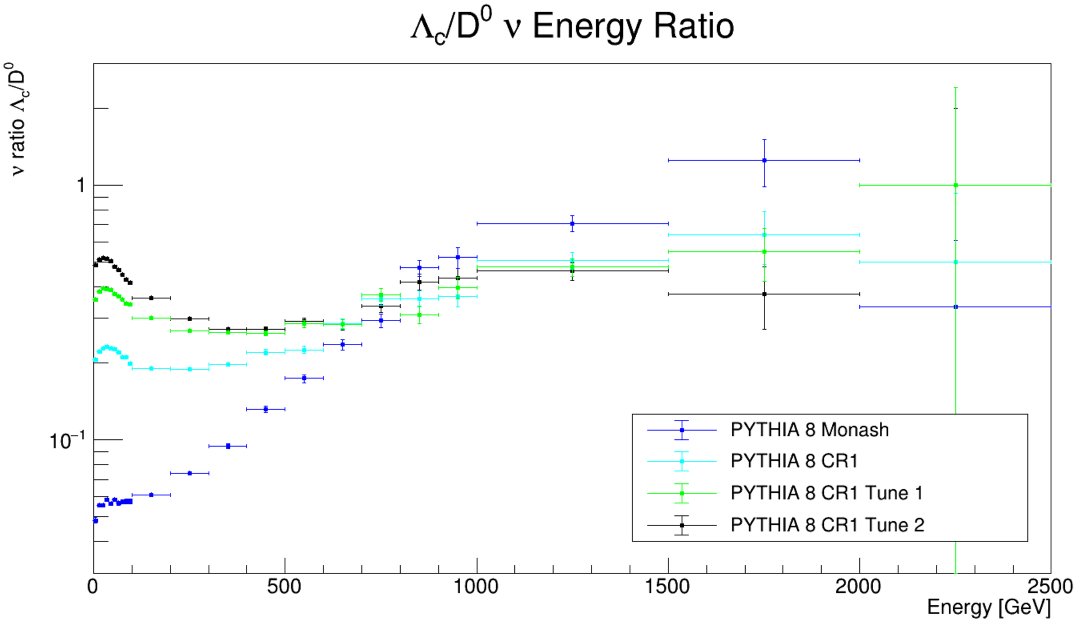

Figure 7: Ratio between Λ_c^+ and D^0 daughter neutrinos as a function of energy.

Overall we are able to tune the baryon-to-meson ratio particularly well using ColourReconnection:mode=1. However the differential cross-section do not agree with data. The agreement was improved for the baryon cross-section while the agreement got worse for the D^0 meson cross-section. Both cross-sections do more or less have the same level of agreement with data while for the Monash Tune the agreement with data is much larger for the meson than for the baryon. The energy shaped is affected by the tunes with the largest differences occurring at energies below 200 GeV. At higher energies it is hard to determine what the difference is due to large uncertainties.

4.3 Colour Reconnection Mode 2

The second set of tunes is based on ColourReconnection:mode=2. As explained in section 3.4 this CR mode works different compared to the other CR modes. All MC results in this section come from 5×10^8 pp collisions at 7 TeV. Similar to the tuning based on CR1 we started with enabling only ColourReconnection:mode. Unlike CR1 colour reconnection mode 2 does not come with a recommended BeamRemnants:remnantmode [10]. As seen in Figure 8 the baryon-to-meson ratio remains virtually identical. The differential cross-section of the D^0 meson agrees less with data for transverse momenta up to 5 GeV/c while it agrees more with data for higher values. Due to large uncertainties however we cannot be completely sure. The total neutrino energy distribution decreases between 0 and 12% for energies lower than 600 GeV. For higher uncertainties become very large but it seems like the ratio will become higher than 1 at higher energies. The importance of the baryon daughter neutrinos is of the same order as in the Monash Tune.

Next ColourReconnection:mode=2 was combined with BeamRemnants:remnantmode=1, which is recommended for CR mode 1 but not necessarily for CR mode 2. In figures and tables this simulation will have the name PYTHIA 8 CR2 Tune 1. This combination of parameters does improve the baryon-to-meson slightly by moving it from 0.05 to approximately 0.10 at very low p_T. The $d\sigma/dp_T$ of the baryon increased slightly between 1 and 3 GeV while for higher p_T it remains the same as for the Monash Tune. The D^0 cross-section is slightly different from the Monash Tune with some values being higher and some being lower. The differences are nevertheless very small and uncertainties overlap. Even though the changes in the ratio and cross-sections are fairly small there are some noticeable differences in the neutrino energy distribution. For energies below 500 GeV the changes vary from 0 to 10% while at higher energies the data points tend to be closer to 1 but with large uncertainties. The relative contribution of the Λ_c^+ for the neutrino distribution is differs from the Monash Tune for energies below 300 GeV. It increased from values between 0.05 and 0.06 to values between 0.08 and 0.10. For higher energies the ratio is slightly lower.

Finally we combined the different Lund parameter in combination with CR mode 2. This tune will be referred to as CR2 Tune 2. The full set of parameters can be seen in Table 2. The Λ_c^+/D^0 ratio increases to 0.16 in the first bin. The ratio is still poorly reproduced after all the tuning. This tune did improve the baryon cross-section slightly with differences slightly less than 0.03 in the first bin. For higher p_T the difference is smaller or nonexistent. The differences in the D^0 meson cross-section are so small that almost all uncertainties overlap. Hence conclusions cannot be taken.

Parameter	**Monash**	**CR2**	**CR2 Tune 1**	**CR2 Tune 2**
ColourReconnection:mode	0	2	2	2
StringPT:sigma	0.335	0.335	0.335	0.335
SringZ:aLund	0.68	0.68	0.68	0.36
StringZ:bLund	0.98	0.98	0.98	0.56
StringFlav:probQQtoQ	0.081	0.081	0.081	0.078
StringFlav:probStoUD	0.217	0.217	0.217	0.2
StringFlav:probQQ1toQQ0join	0.5, 0.7 0.9, 1.0	0.0275 (4x)	0.0275 (4x)	0.0275 (4x)
MultiPartonInteractions:pT0Ref	2.28	2.28	2.28	2.15
BeamRemnants:remnantMode	0	0	1	1
BeamRemnants:saturation	-	-	5	5

Table 2: Parameter settings for tunes based in ColourReconnection:mode=2.

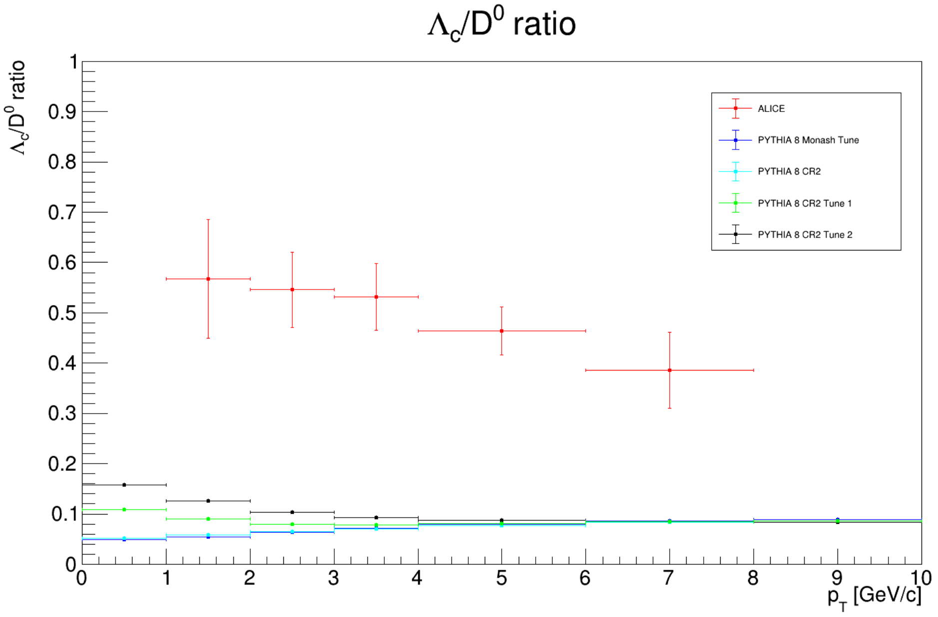

Figure 8: The Λ_c^+/D^0 ratio as a function of transverse momentum (p_T) for different simulations compared to ALICE data [1]. The Monash Tune is the standard version of PYTHIA 8. PYTHIA 8 CR2 is with solely CR mode 2, PYTHIA 8 CR2 Tune 1 is CR2 with RemnantMode 1 and PYTHIA 8 CR2 Tune 2 has different Lund Parameters and quark decay probabilities.

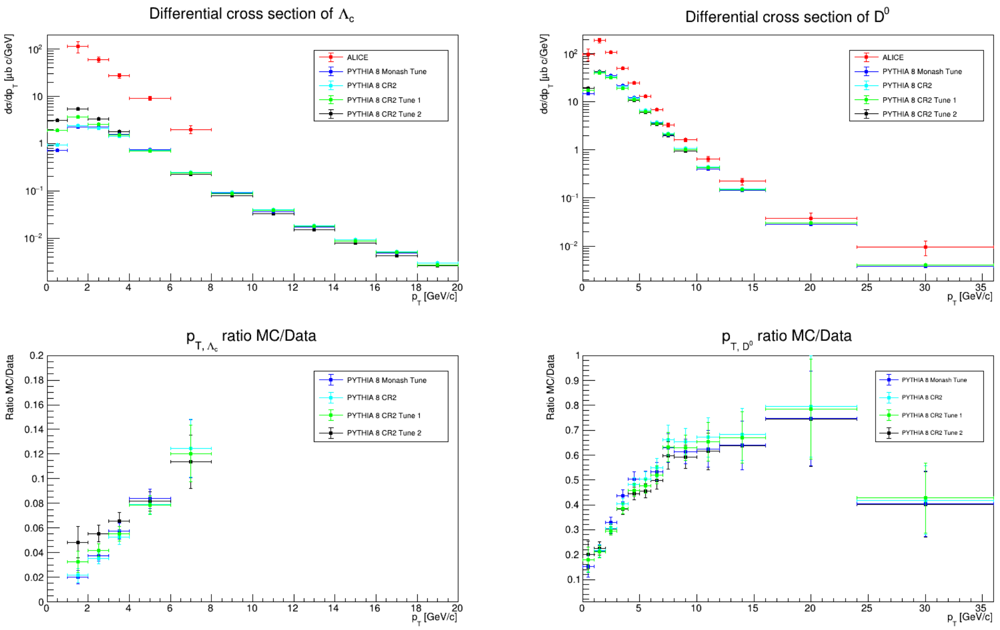

Figure 9: Upper: Differential cross-section for Λ_c^+ baryons and D^0 mesons at central rapidity $\eta < 0.9$ compared to ALICE data [13], [1]. Lower: Ratio MC/Data.

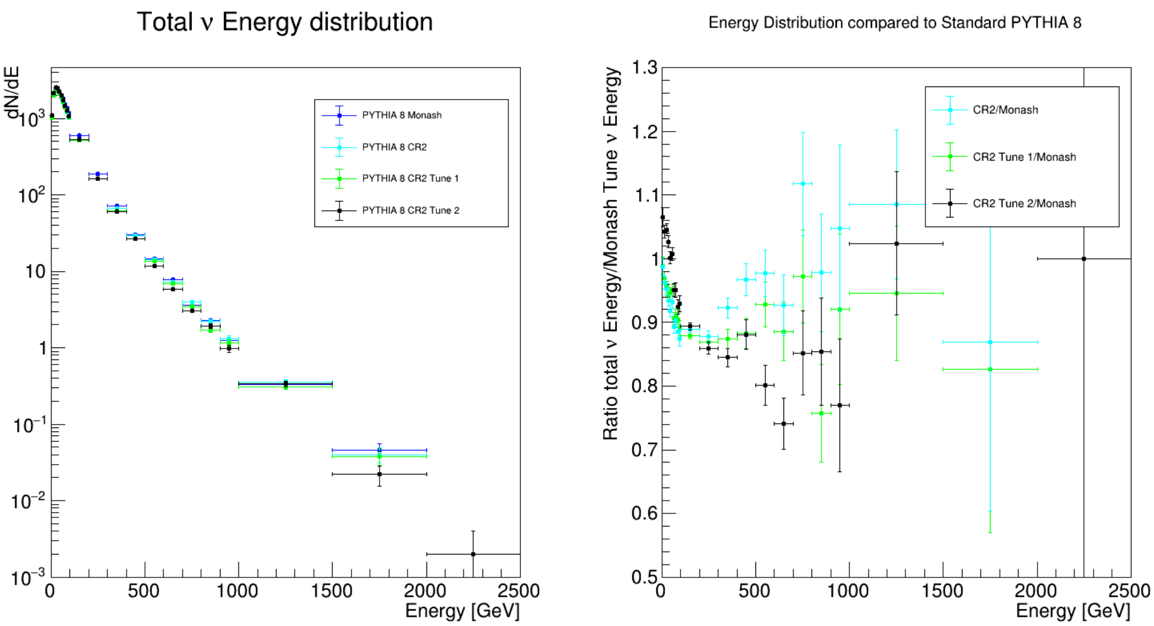

Figure 10: Left: Total energy distribution of both Λ_c^+ and D^0 daughter neutrinos at forward rapidity $\eta > 5$. Right: Ratio between Λ_c^+ and D^0 daughter neutrinos.

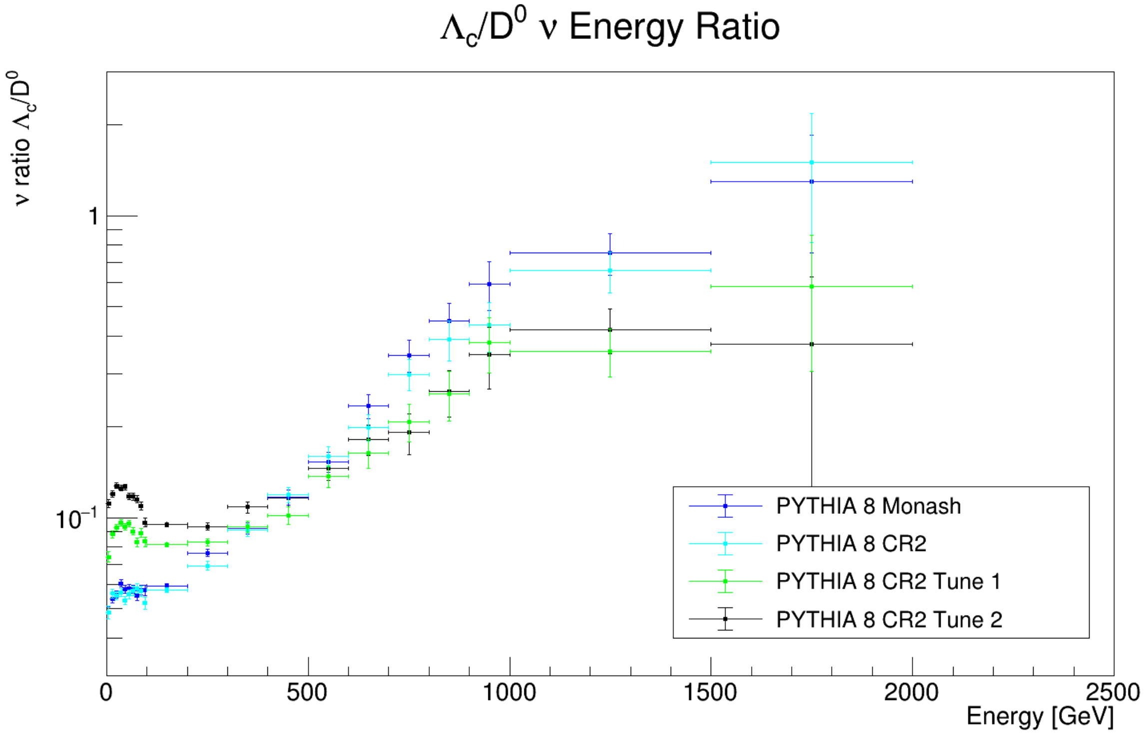

Figure 11: Ratio between Λ_c^+ and D^0 daughter neutrinos as a function of energy.

Overall the tunes based on CR mode 2 were not successful. Neither the baryon-to-meson ratio or the differential cross-sections agree in some form with data. Even though the impact on the neutrino energy distributions was larger these findings cannot be used to modify the IceCube background signal.

4.4 Limited statistics at higher energies

Even though the ratio was quite accurately reproduced in CR1 Tune 2 it is hard to draw specific conclusions for the neutrino energy distribution because the uncertainties above 700 to 800 GeV become large enough to forbid any firm conclusions. Since IceCube studies neutrinos at energies at the TeV scale an improvement in statistics is required. We tried gaining more statistics in the higher energy region using PhaseSpace:pTHatMin. With changing this value from 0 to any positive value x the minimum energy exchanged in parton interactions is at least x GeV. This does however change the differential cross-sections in an unphysical way. Ratios are still reproduced as without this command because both factors of the ratio are affected in the exact same way. We chose PhaseSpace:pTHatMin = 200 GeV. Due to time limitations this was only done for CR1 Tune 2, which was the most accurate tune. As seen in Figure 12 the ratio is identical to the one in Figure 4.

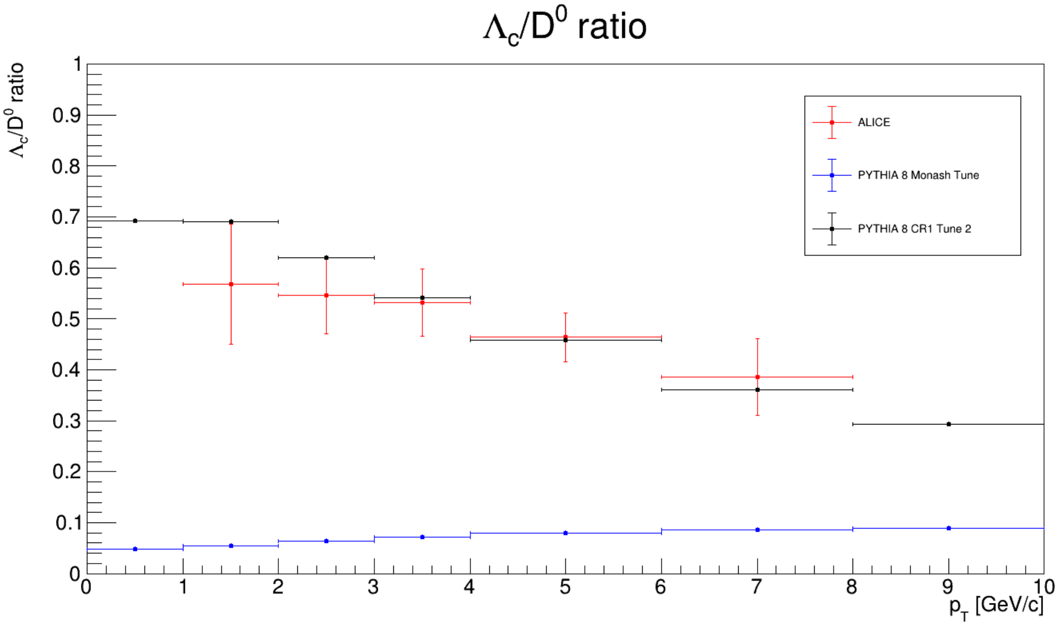

Figure 12: Λ_c^+/D^0 ratio from the enhanced collision compared to the Monash Tune and ALICE data [1].

Unfortunately this does not improve statistics as expected. Above 2500 GeV there are 0 entries for all the neutrinos as can be seen the figure below.

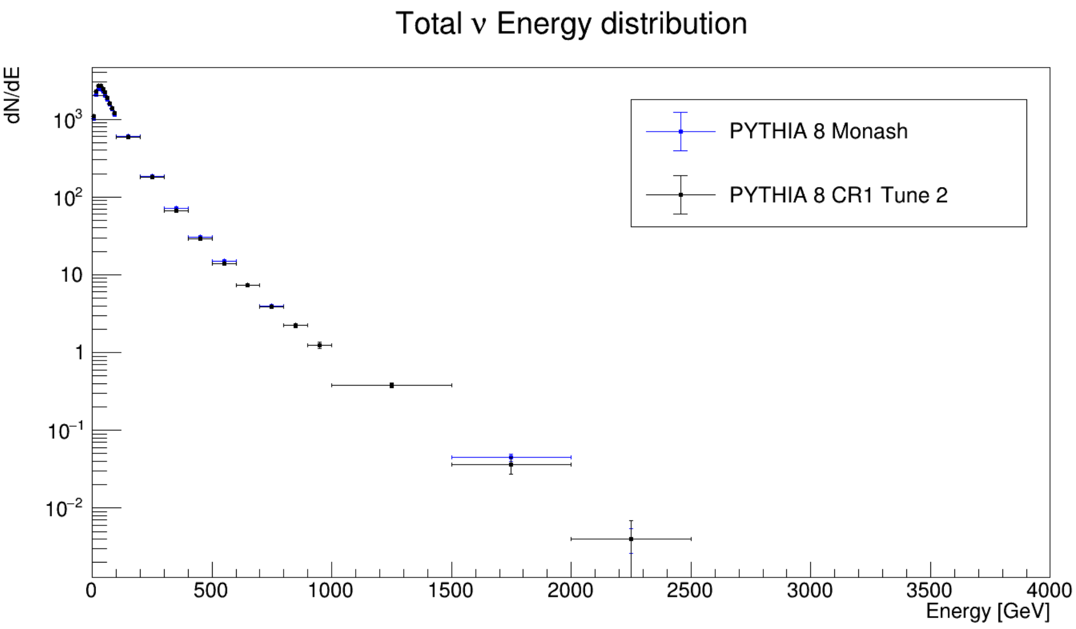

Figure 13: Neutrino energy distribution for CR1 Tune 2 with enhanced parton interactions at a minimum of 200 GeV.

5 Conclusion, Discussion & Outlook

5.1 Conclusion & Discussion

The results presented in this thesis prove that Pythia8 is able to reproduce the Λ_c^+/D^0 ratio by combing CR mode 1 with different Lund parameters and adjusting the CR mode parameters. However the differential cross-sections are still poorly reproduced. This suggests that there is an additional physics process that determines the momentum distributions of the baryons and meson. This process is not fully understood. Compared to the Monash Tune the agreement between the ALICE measurement and simulations in terms of the differential cross-section of the Λ_c^+ improved between 20 and 30% with the largest improvements occurring at higher p_T. The differential cross-section of the D^0 meson agrees around 10% less with data when compared to the D^0 cross-section of the Monash Tune. Changes up to ±10% in the neutrino energy distribution are observed but we are unable to draw conclusions for the energy scales above 600 GeV due to large uncertainties. For energies below 100 GeV there is an increase while between 100 and 600 GeV there is a decrease in the neutrino energy distribution. Furthermore we can see that tuning CR mode 2 in a similar way does not lead to the desired result. Even though the changes in ratio are much smaller compared to CR mode 1 the difference in the neutrino energy distribution is larger. Hence there isn't a linear relation between the baryon-to-meson ratio and the neutrino energy shape. In general the amount of statistics in the higher energy region is too low, which was not solved within the available time. The results prove that our initial hypothesis is indeed correct. The changes in the baryon-to-meson ratio compared to results from e^+e^- collisions has an effect on the energy shape of the neutrinos at forward rapidity ($\eta > 5$). However the limited statistics collected does not allow to draw firm conclusions for the neutrino energy shape at the TeV scale.

5.2 Outlook

Even though the Λ_c^+/D^0 ratio is well reproduced by Pythia8 the differential cross-sections on the other hand still do not agree with data. There have been improvements between 20 and 30% for the Λ_c^+ but at the same time the D^0 cross-section shows worsening of the agreement with data of about 10%. Further tuning can be done in order to improve these. It may be worth to try applying different beam remnant modes and tuning their parameters. On top of that other parameter sets can be modified such as the MultiPartonInteraction parameters. A Parton Distribution Function (PDF) set determines the probabilities to find a certain parton as function of its momentum fraction inside a proton. Hence it may be worth trying PDFs obtained from different measurements. A clear point what should be considered for further analysis is the amount of statistics that can be generated in the simulation. We reported results using simulation samples of 2 billion events and we clearly proved those are allowing to investigate the neutrino energy shape only up to 2.5 TeV. Therefore it can be anticipated that, in order to investigate a significantly higher energy range (>10 TeV) we would need samples of the order 10^{17}, which is estimated as described in the Appendix. The estimation likely overshoots the required number of events but it shows that it is beyond practical limits. Within practical limitations it is possible to run 10^{11} or 10^{12} events at maximum. Hence the study of high energetic neutrinos is limited at energies around 1.5 TeV when simulating 7

TeV collisions. Note that this value corresponds to a 10% uncertainty at 1.5 TeV and is therefore lower than the 2.5 TeV limit observed in this thesis. On top of that it may be possible that the function fit is not completely accurate and therefore the energy limit is underestimated. Nevertheless the maximum observable energy with a 10% uncertainty is much lower than the desired value of 10 TeV. Furthermore it is interesting to investigate if it may be possible to find a way to simulate only the processes of interest and not the full collisions, saving time and disk space. It could also be interesting to see what the results would be if the same tunes were applied at collisions at 13 TeV for example. Data from these collisions is already available. Collisions between other hadrons such as p-Pb, Pb-Pb or Au-Au can be simulated and compared with data as well. Finally it may be interesting to simulate collisions at energies between 20 and 50 TeV because that is the typical energy of hadron-hadron collisions in the atmosphere. This would massively increase the neutrino energies.

A Appendix

An estimation for the required number of events in order to have 10% uncertainties at 10 TeV was made. First the neutrino energy shape of the Monash tune and CR1 Tune 2 were fitted by an exponential of the form $dN/dE = d * \exp[\frac{a*x+b}{c}]$ as can be seen in Figure 14. Here a, b, c and d are the fit parameters. The fit was performed on the interval 50 to 10000 GeV to allow for a reasonable fit within time limitations. Then the function was evaluated at 10 TeV and divided by 2×10^9 to obtain the dN/dE per single event (P). To obtain the dN/dE for a given number N we just have to multiply P by N. This quantity was arbitrarily given the letter M. Since the uncertainty is simply $\sqrt{binvalue} = \sqrt{M}$ and we want a 10% uncertainty we can determine $\sigma_M/M = 1/\sqrt{M} = 0.1$ and rewrite the equation for the required events N. Then $N = 100/P$.

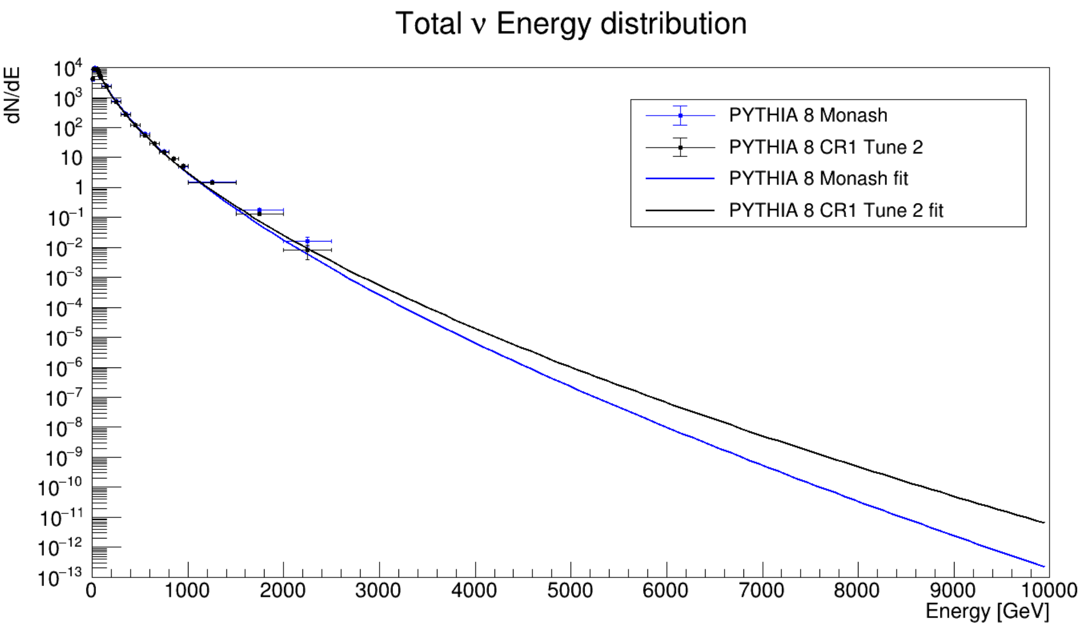

Figure 14: Neutrino energy shapes and their exponential fits of the form $dN/dE = d * \exp[\frac{a*x+b}{c}]$.

When P is obtained for the CR1 Tune 2 fit the required number of events to have a 10% uncertainty at 10 TeV is 1.96621×10^{17} which is in the order of 10^8 as many events compared to what was done in this thesis. In practise it is not possible to run this many events and therefore it is not possible to study the neutrinos at 10 TeV using this collision energy. The upper limit that can be ran in a reasonable time is in the order of 10^{11} events. From the fit we can also determine the maximum energy value we can observe with a 10% uncertainty with a given number of events. Since $P = A/(2 \times 10^9)$ with A the fit value at a certain energy one can determine that $A = 10^{11}/N$. Hence A = 1 if the maximum amount of events is 10^{11}, which corresponds to a maximum observable energy of 1208.34 GeV. The largest energy that can be observed with 10% uncertainty is given for different NeVs in the table below. Here the fit to CR1 tune 2 is used.

Number of events	**Maximum observable energy with 10% uncertainty in GeV**
10^{10}	801.63
10^{11}	1208.34
10^{12}	1638.24
10^{13}	2226.05
10^{14}	2831.15

Table 3: The maximum observable energy with 10% uncertainty. For higher energies the uncertainties would become larger than 10%.

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