Universiteit Utrecht

Opleiding Natuur- en Sterrenkunde

Strangeness production as a function of multiplicity in pp collisions with PYTHIA

Bachelor Thesis

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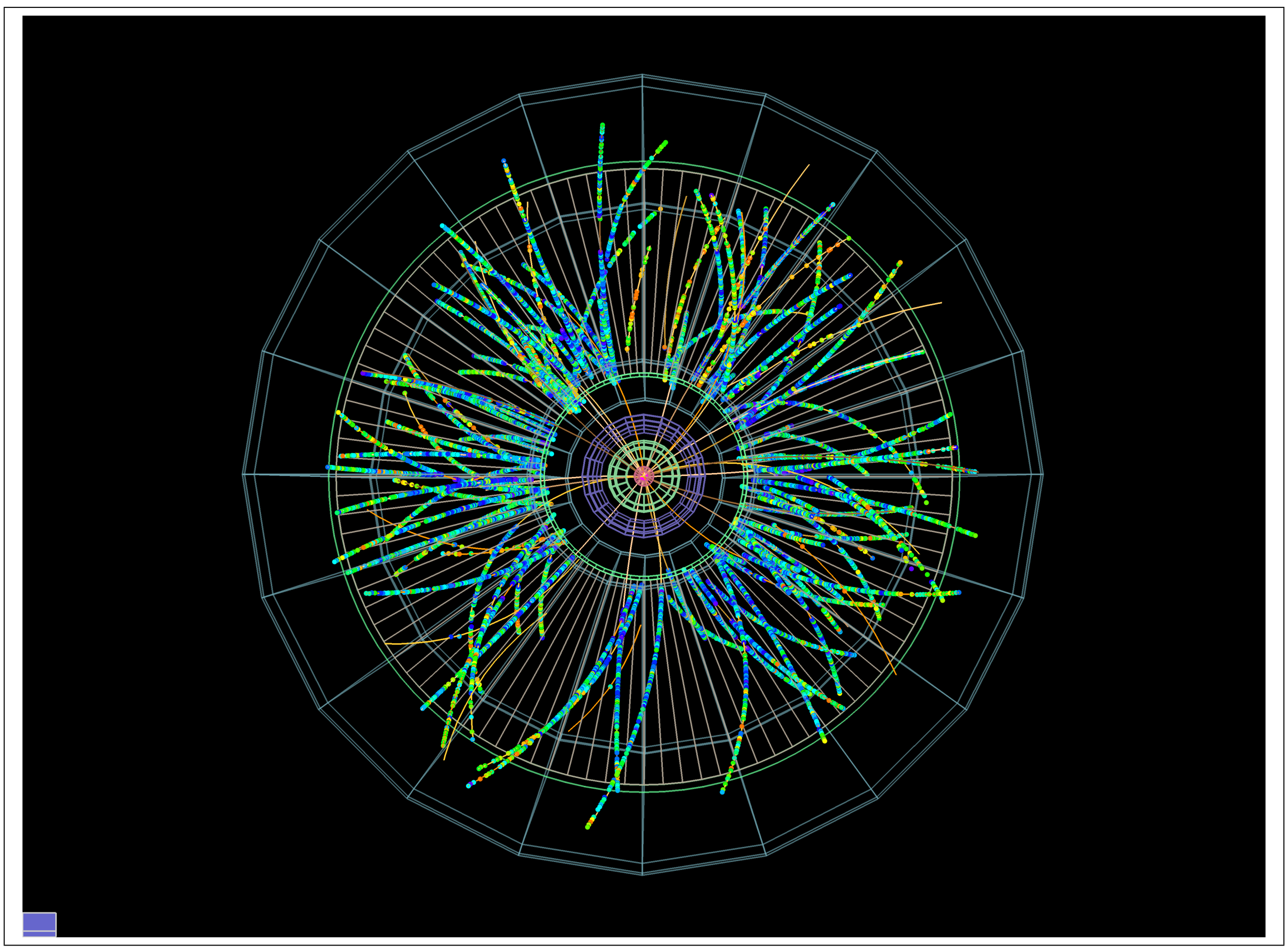

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Abstract

The description of the Quark Gluon Plasma can bring extra insight into the early universe and can increase understanding of the strong force in the standard model. This thesis analyzes data from PYTHIA-generated proton-proton collisions with and without Color Reconnection in order to ascertain whether Color Reconnection could explain some of the findings attributed to the formation of a QGP in High-Energy particle collisions.

The thesis finds that Color Reconnection can qualitatively achieve similar results as are found in high-energy proton collisions. This implies that there might be a different explanation than a de-confined state of matter for the particle behavior that is found experimentally. The mechanism behind this could be Color Reconnection.

Contents

1 Introduction

The standard model of particle physics is the broadest and most unifying theory that physics has produced as of yet. It includes the weak, the strong and the electromagnetic force, only failing in describing the force of gravity. In the standard model, the accurate description of the Quark Gluon Plasma (QGP) is one of the top priorities for particle physicists at this moment. Its study provides grounds to understand the strong interaction, early universe phenomena and astrophysical processes [1].

It has been expected and shown [1] that a QGP is formed in heavy ion collisions at the BNL and CERN high- collisions in order to understand the nature of the QGP. However, phenomena similar to those occurring due to the formation of a QGP have also been reported lately in high-multiplicity proton-proton (pp) collisions [2]. This is unexpected *-and therefore interesting with respect to improving upon the standard model-* because the size of the collision in pp was long thought to be too small to create a QGP [2].

This thesis aims to investigate the possibility of alternative processes than the creation of a deconfined phase that could explain these latest experimental results. This aim is pursued by studying and describing the behavior of pp collisions at an energy of *7 TeV center of mass energy* in the Monte Carlo (MC) event generator PYTHIA 8. Its main focus is to describe the effect of Color Reconnection (CR) on pp collisions, in order to ascertain whether this gives QGP like effects.

The thesis is guided by the following research questions: *Does Color Reconnection enhance Strange particle production as a function of multiplicity?* and *Does Color Reconnection addition to PYTHIA enhance QGP phenomena in rendered pp collision events?*

This thesis finds qualitative reasons that imply CR might be one of the mechanisms that bring about phenomena attributed to the QGP phase.

In order to be able to understand the results correctly, there will first be a theoretical description entailing a short review of the standard model, a description of pp collisions and a theoretical perspective on Color Reconnection. Hereafter the analysis method will be elaborated on and the results will be explained. Lastly there will be sections with the conclusions and discussion of this thesis.

2 Theory

The standard model of particle physics is fundamental to understanding the structure and behavior of matter. It describes three out of four fundamental forces known at this time: the electromagnetic, the weak and the strong force. As of yet the standard model is not able to describe the gravitational force. Also, it classifies elementary particles, which are divided into elementary fermions (the (anti-)quarks and (anti-)leptons) and elementary bosons (the gauge bosons and the scalar bosons), an overview is given in Figure 1. Each of the described forces is carried by one of the gauge bosons: the strong force is carried by the gluons, the electromagnetic force is carried by the photon, and the weak force is carried by the Z- and W- bosons. An overview of the interactions is shown in Figure 2.

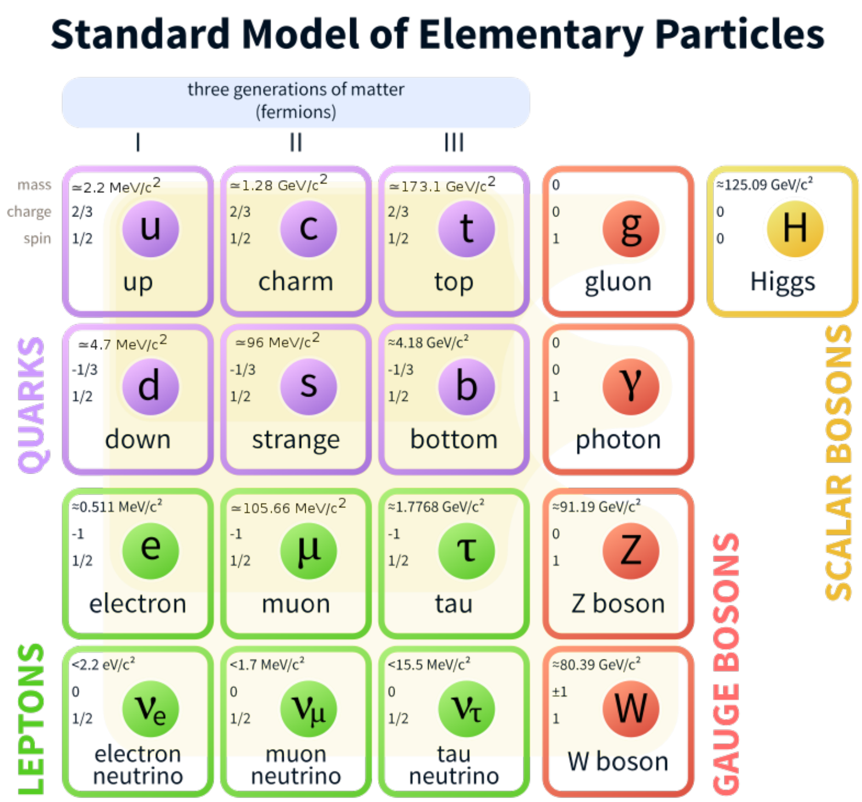


Figure 1: The Standard Model of Particle Physics visualized [5]

The (anti-)quarks and the gluons of the standard model are prone to a phenomenon called color confinement. This phenomenon causes quarks in normal conditions to be very strongly bound to one another, and only to be encountered in color singlet particles (hadrons). Hadrons are then split up into mesons (quark-anti-quark pairs) and baryons (three-quark pairs). These interact via the strong-, the electromagnetic- and the weak forces.

The (anti-)leptons follow a different pattern: The electron, muon and tau are charged and thus interact via the electromagnetic- and weak forces. The neutrinos are not charged and only interact weakly.

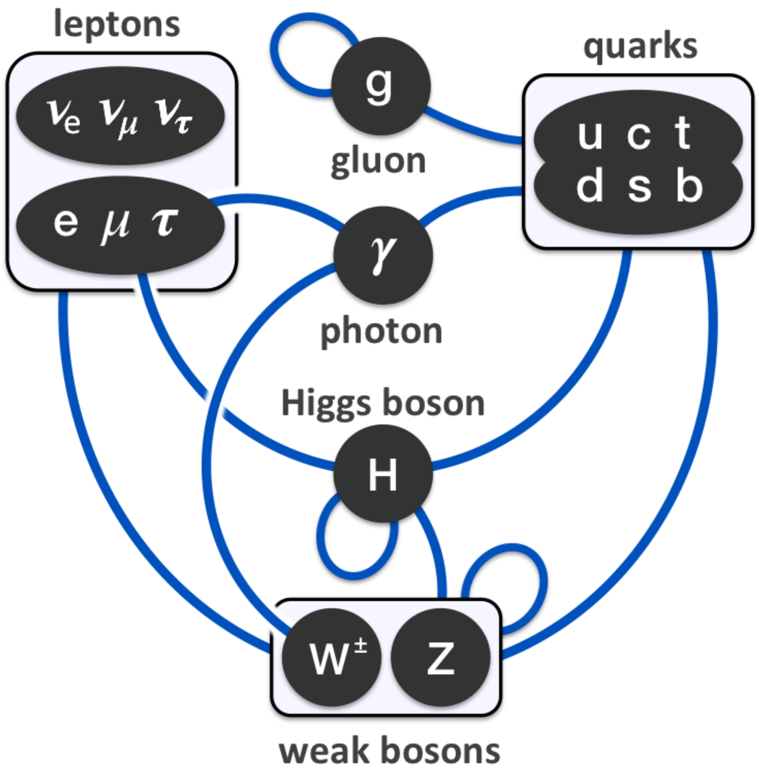


Figure 2: The interactions of the Standard Model of Particle Physics visualized, from [10]

The focus of this thesis is mainly on interactions of the strong force. The theory that describes the strong force is Quantum Chromo Dynamics (QCD). QCD is a non-Abelian quantum field theory. Its force carrier is the gluon, and it has an analog to electric charge in QED, namely color charge. The theory of QCD exhibits color confinement, on the other hand it also exhibits asymptotic freedom. The latter describes that, as the energy scale of interactions increases, there is a steady reduction in the strength of interaction between quarks and gluons [1].

2.1 Quark Gluon Plasma

In nature, hadrons come as color singlet states. Adding pressure to hadrons causes the quarks and gluons in them to eventually deconfine and give rise to a QGP: A state wherein quarks and gluons can overcome color confinement and move freely within other particles without color charge [1][3]. Figure 3 shows the phase diagram of QCD. It is worth noticing that at this moment the QGP is not directly measurable due to its very short lifetime. Its behavior is well described by relativistic viscous hydrodynamics and its anisotropic flow points to the QGP being a superfluid [4]. The QGP is expected to form in the interior of neutron stars and it is found to be produced in high energy collisions. Studying the QGP is mostly done by

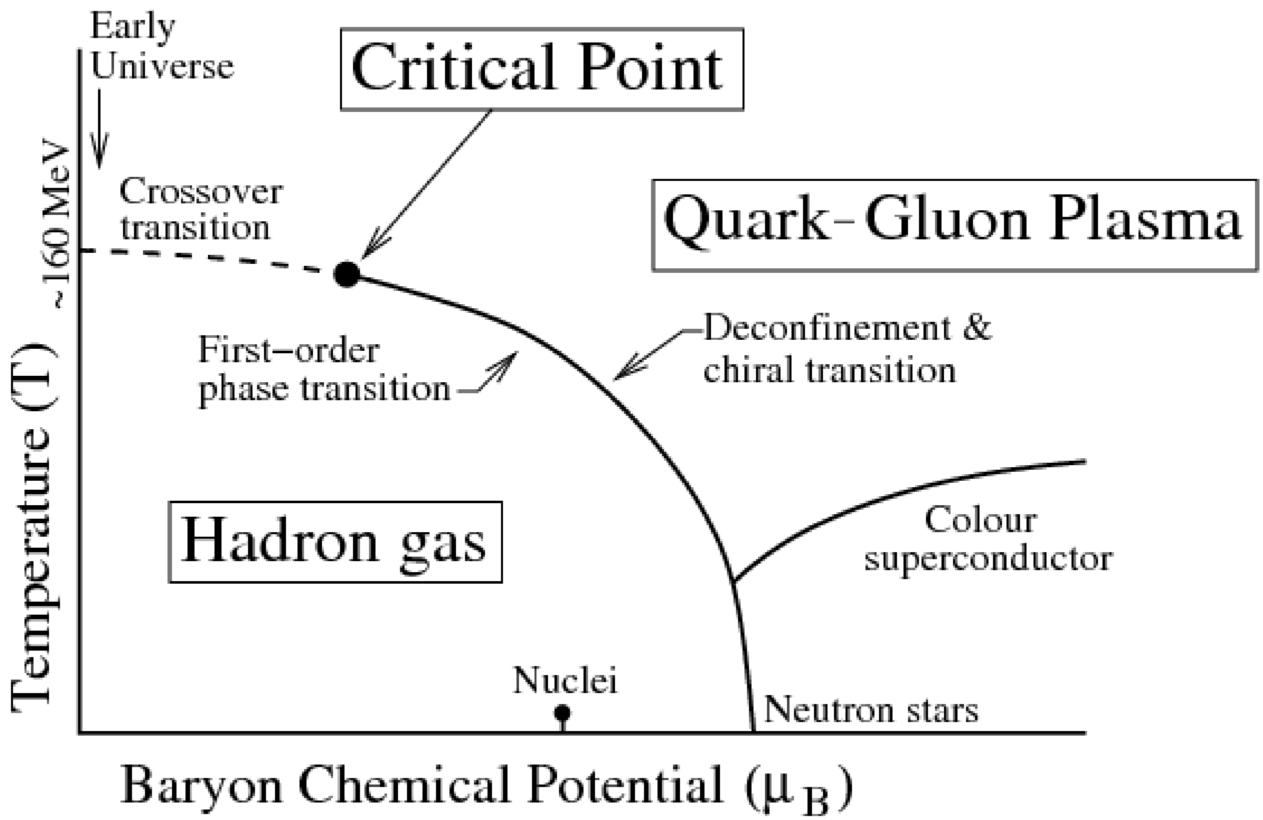


Figure 3: Baryon Phase diagram from [9]

investigating heavy ion collisions at accelerators such as the LHC. Recent findings however, imply that a QGP might also be formed in high multiplicity pp collisions [2].

2.2 Proton-Proton collisions

Collisions between proton beams serve various purposes in physics. The multiple TeV center of mass energy at which protons are collided at the LHC, serve mostly for trying to find physics beyond the standard model. This thesis will focus on the possibility of using pp collisions to create a QGP.

The center of mass energy reached for proton-proton collisions at this moment is 13 TeV at the LHC. The collided protons at this energy travel at very nearly the speed of light and are thus prone to relativistic effects. The Pythia 8 model this thesis works with, has a center of mass energy of 7 TeV. That means that 7 TeV is available for particle production. Only a part of this energy is really used for particle/mass production. The remainder goes to the created particles longitudinal and transverse momentum.

2.3 Color Reconnection

The mechanism of CR is the phenomenon of multiple hard subcollisions due to color string formations between final partons from independent hard scattering [3]. It results in a picture where an excited particle moving away will drag along other particles by forming color connections with them. The process is visualized in 4. This produces a flow-like effect that increases transverse momentum -p_{T}- with higher multiplicity. This effect is also strengthened as a function of particle mass. If CR is turned off, the bindings just disappear and no such thing happens [3].

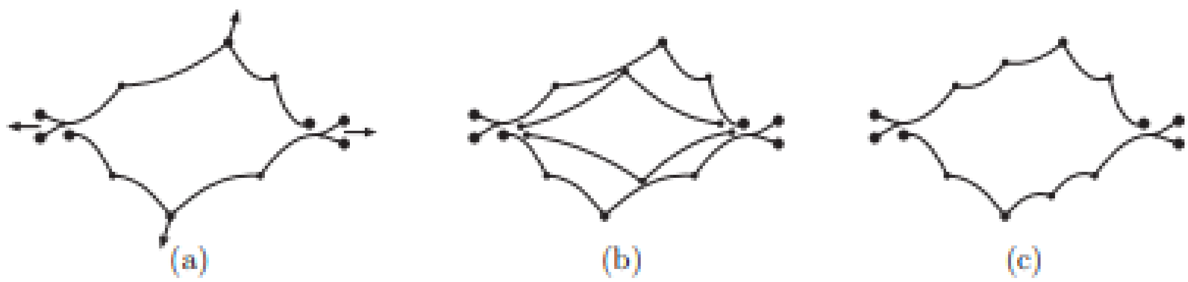


Figure 4: color reconnection shown graphically from [8]

3 Analysis

3.1 Data Sample

The data sample for this thesis is generated using the PYTHIA 8 generator. PYTHIA is a Monte Carlo (MC) program for the generation of high-energy particle collisions events, it is written in C++ **??**. PYTHIA contains theories and models for a number of physics aspects, including hard- and soft interactions, parton distributions, initial- and final-state parton showers, multiparton interactions, fragmentation and particle decay [3][7]. It is a model that is widely used for generating and describing pp collisions.

This thesis uses two PYTHIA-generated datasets. One data-set for pp collisions with CR, and one for pp collisions without CR (denoted as NOCR from now on). Both datasets are run for a center of mass energy of$\sqrt{s} = 7$ TeV. Both datasets contain a number of events in the order of 10^7. The exact number is shown in this table.

$\eta \leq 0.8$	nr. of events in dataset
NOCR	7.2×10^7
CR	8.4×10^7

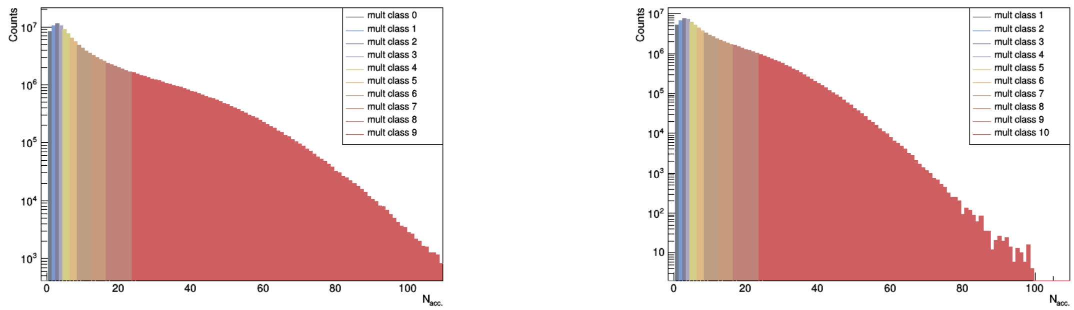
Table 1: Number of events in datasets.

ALIROOT *-the CERN software package to analyze data-* was used to analyze the datasets. This package works with the CINT C++ interpreter.

3.2 Methods

This thesis focuses on the production of primary particles of various species as a function of multiplicity class, but also without any multiplicity selection (referred to as minimum bias further in the text). The multiplicity classes are defined as shown in 5.Every multiplicity class spans around 10 percent of the events. The multiplicity distribution for CR has a smaller multiplicity range than the one for no CR. The mean multiplicity for every class is thus somewhat higher for NOCR. Only primary particles were considered in this thesis, produced within a given pseudorapidity (η) window.

This research focuses on the findings of the $|\eta| \leq 0.8$ datasets. The difference between the $|\eta| \leq 0.8$, $|\eta| \leq 1.6$ and $|\eta| \leq 2.4$ cuts is only of a scalar nature. The $|\eta| \leq 0.8$ cut is the most suitable for this thesis because it is the same as the ALICE detector is restricted to. All plots are drawn with error bars and the particle species analyzed are shown in Table 3.



(a) Multiplicity class definition for NOCR $\eta \leq 0.8$. (b) Multiplicity class definition for CR $\eta \leq 0.8$.

Figure 5: Plots showing the 10 multiplicity classes and the multiplicity values they represent

multclass	NOCR multiplicity cut	CR multiplicity cut	rough percentage of events
1	0-3	0-3	90-100
2	4-4	4-4	80-90
3	5-5	5-5	70-80
4	6-7	6-6	60-70
5	8-10	7-8	50-60
6	11-13	9-10	40-50
7	14-18	11-14	30-40
8	19-26	15-18	20-30
9	27-38	19-25	10-20
10	39-10000	26-10000	0-10

Table 2: multiplicity class definition

pdgcode	particle	strange quarks	mass in MeV/c^2
211	$\pi^{\pm}$	0	139.57
2212	$\overline{\mathrm{p}}$	0	938.27
310	K_{s}^{0}	1	497.61
321	$K^{\pm}$	1	493.67
3122	Λ	1	1115.68
3322	Ξ^{0}	2	1314.86
3312	$\Xi^{\pm}$	2	1321.71
3334	$\Omega^{\pm}$	3	1672.45

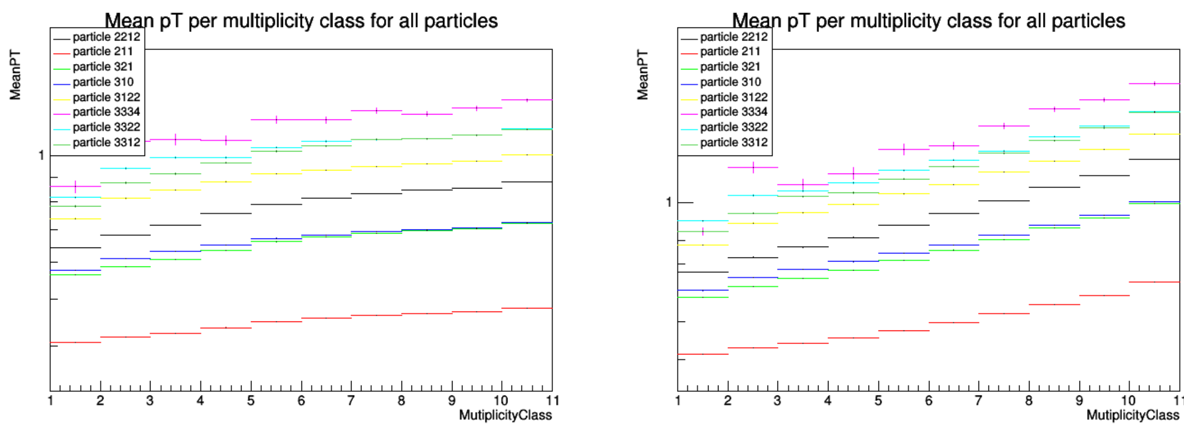
Table 3: The analyzed particles and some of its properties, from

4 Results

The result section is structured in the way that the plots without Color Reconnection (NOCR) are shown on the left, and the plots with Color Reconnection (CR) are shown on the right. This is also described in the captions.

4.1 Mean Transverse Momentum Versus Multiplicity Class

The histograms in Figure 6 show the value of of the mean transverse momentum p_{T} defined as $p_{\mathrm{T}} = \sqrt{p_{\mathrm{x}}^2 + p_{\mathrm{y}}^2}$, as a function of multiplicity class, for every particle. It is clear that every particles' mean p_{T} rises with multiplicity class, yet in the CR case 6b, the rise with multiplicity class appears to be a lot steeper than in the NOCR case 6a. This indicates that there might be a boost the particles feel that is dependent on multiplicity, which is also what one would expect with CR (and similar to what one expects from the creation of a QGP).



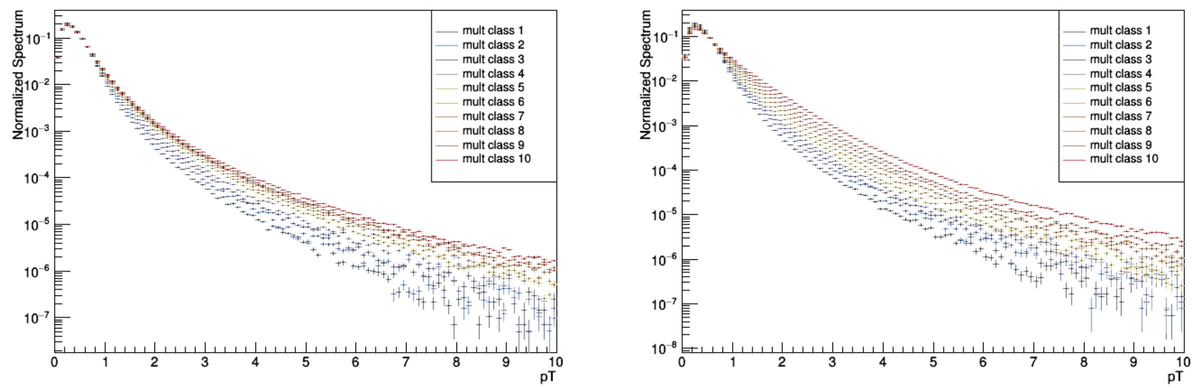
(a) NOCR. (b) CR.

Figure 6: This figure shows the Mean p_{T} vs. multiplicity class for all analyzed particles. Both the NOCR and the CR show a rise in p_{T} with multiplicity class. In the CR case this dependence looks steeper than in the NOCR case.

4.2 Transverse Momentum Spectra Versus Multiplicity Class

In these plots, the normalized spectra of all analyzed particles are shown. Moreover, the minimum bias plots are shown. The general trend is clear: higher multiplicity classes have relatively more particles with higher momenta than the lower multiplicity classes. It is apparent that the distinction is more pronounced with CR than without CR. This is also an effect that is expected from the formation of a QGP at higher multiplicity, driven by initial pressure gradients which boost those particles [4]. Some heavier particles have a lack of statistics and thus Ω is excluded for that reason, but the trend is clear.

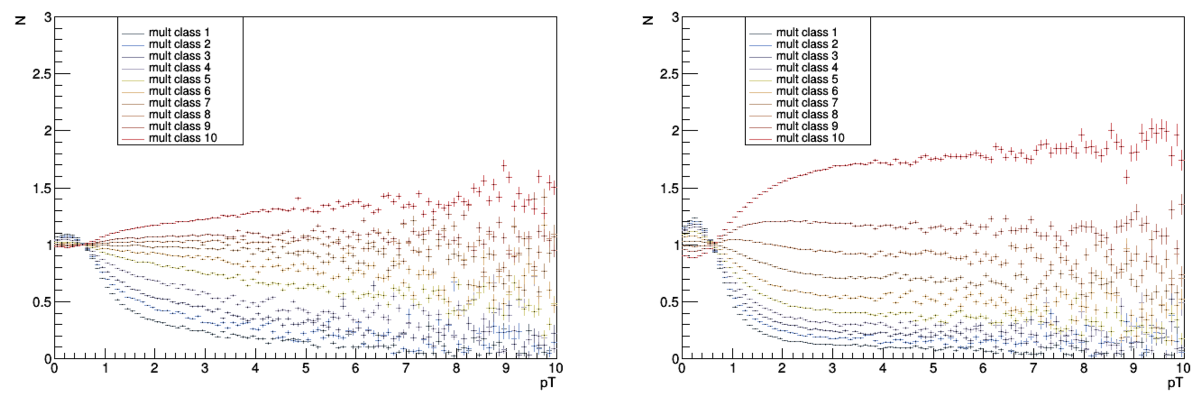
The minimum bias plots -*the plots where no multiplicity selection is made*- show every single multiplicity class spectrum, divided by the whole spectrum of that particle. These histograms show the distinction between CR and NOCR even clearer, as the spacing between the lines is a lot bigger for CR and for NOCR and the effect is more pronounced with higher p_T.



(a) NOCR:pion spectrum.

(b) CR:pion spectrum.

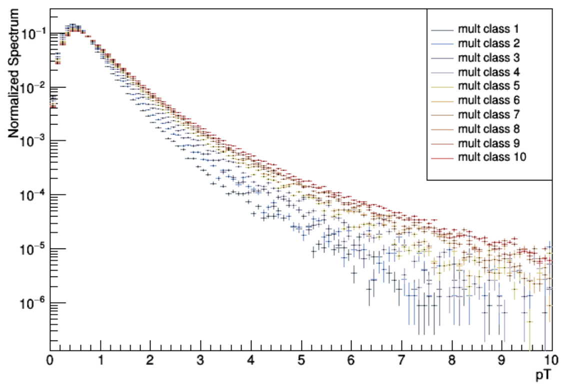
Figure 7: Normalized spectra of pions.



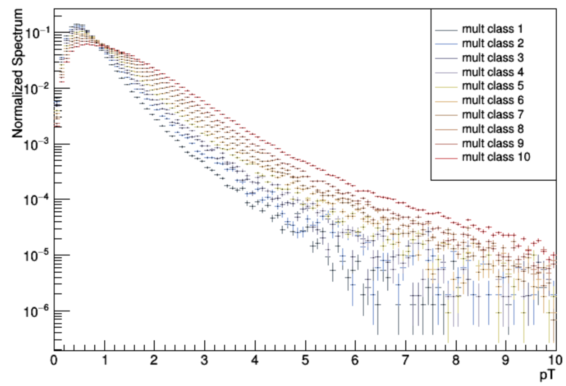
(a) NOCR: pion minimum bias.

(b) CR: pion minimum bias.

Figure 8: These plots show the normalized pion spectra 7a 7b and and the corresponding minimum bias 8a and 8b. The plots show clearly that the difference in spectra between the multiplicity classes is a lot more pronounced with CR.

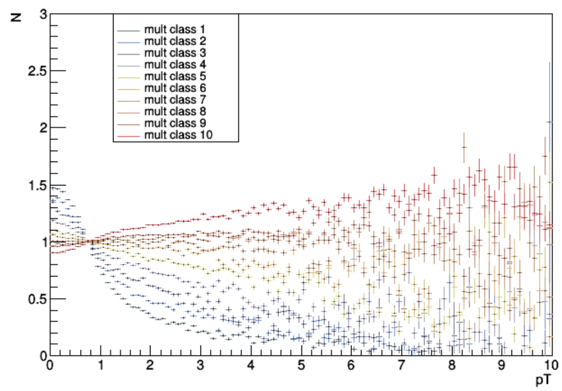


(a) NOCR: proton spectrum.

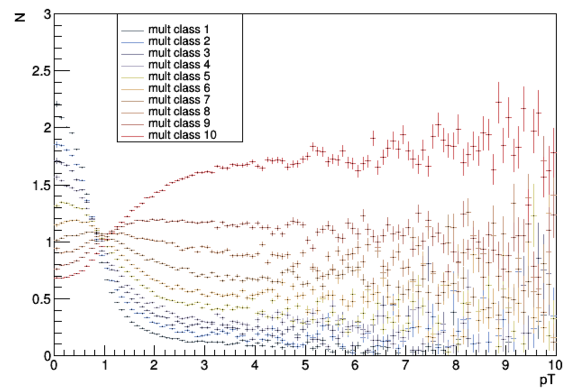


(b) CR: proton spectrum.

Figure 9: Normalized spectra of protons

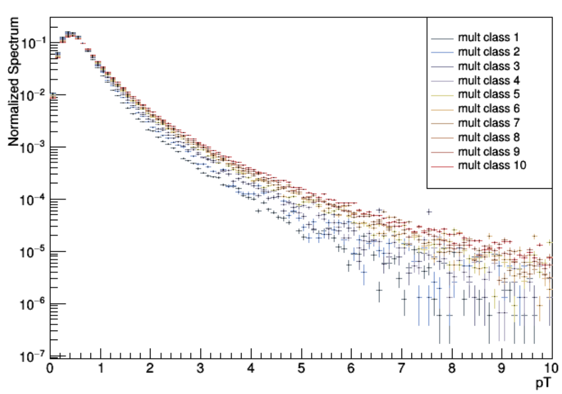


(a) NOCR: proton minimum bias.

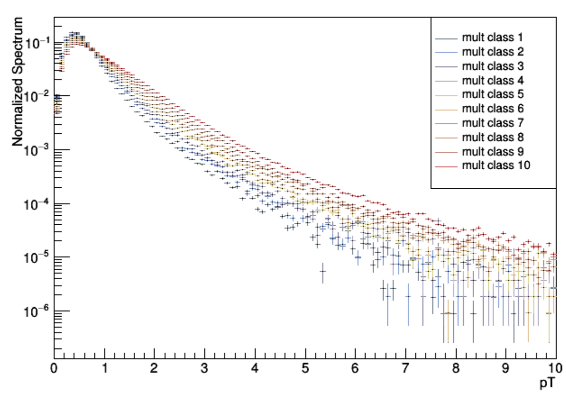


(b) CR: proton minimum bias.

Figure 10: These plots show the proton spectra 9a and 9b, and the corresponding minimum bias 10a and 10b. The plots show clearly that the difference in spectra between the multiplicity classes is a lot more pronounced in CR.

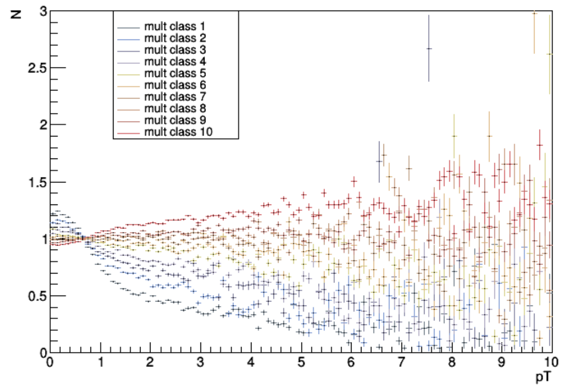


(a) NOCR: K_s^0 spectrum.

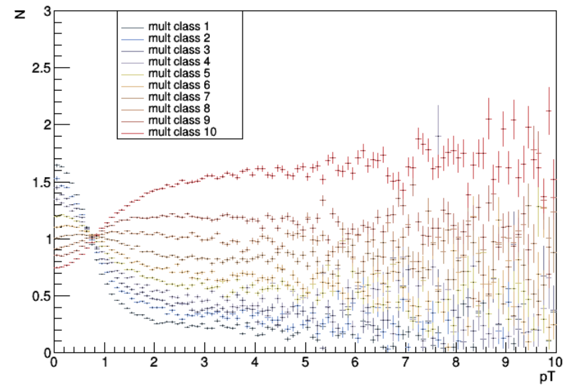


(b) CR: K_s^0 spectrum.

Figure 11: Normalized K_s^0 spectra.

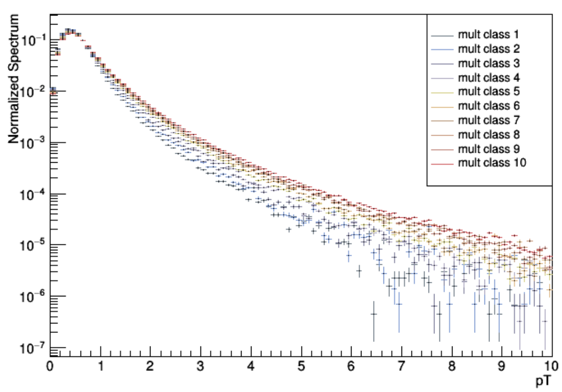


(a) NOCR: K_s^0 minimum bias.

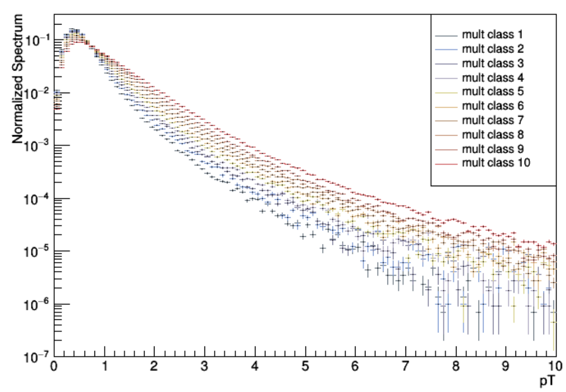


(b) CR: K_s^0 minimum bias.

Figure 12: These plots show that, also for K_s^0s,the difference in spectra between the multiplicity classes is a lot more pronounced in CR

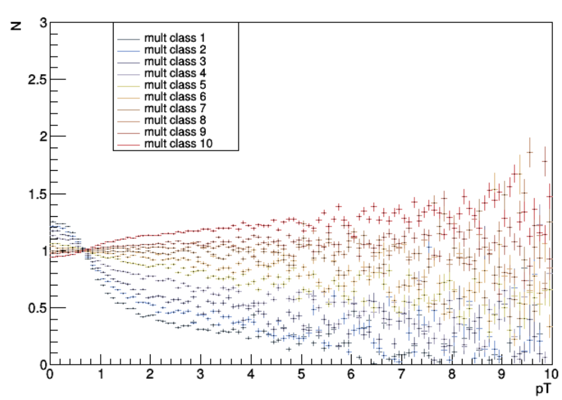


(a) NOCR: $K^{\pm}$ spectrum.

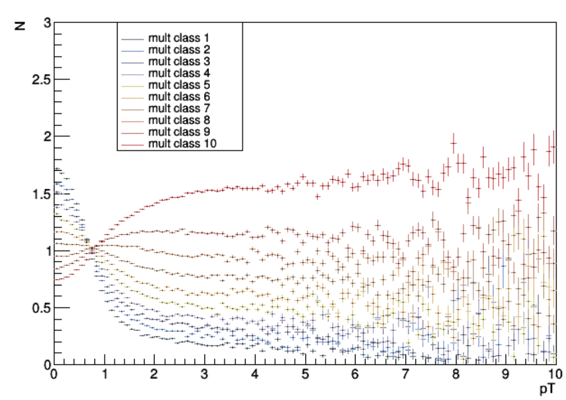


(b) CR: $K^{\pm}$ spectrum.

Figure 13: Plots of Normalized $K^{\pm}$ spectra.

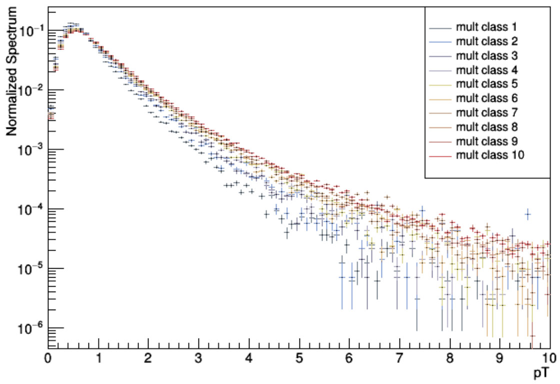


(a) NOCR: $K^{\pm}$ minimum bias.

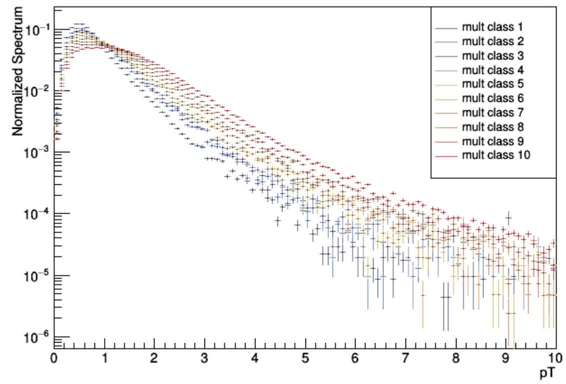


(b) CR: $K^{\pm}$ minimum bias.

Figure 14: The plots of the spectra show that higher multiplicity values have a harder spectrum. Comparing NOCR to CR for every plot, also reveals that this difference between the multiplicity classes is enhanced for CR.

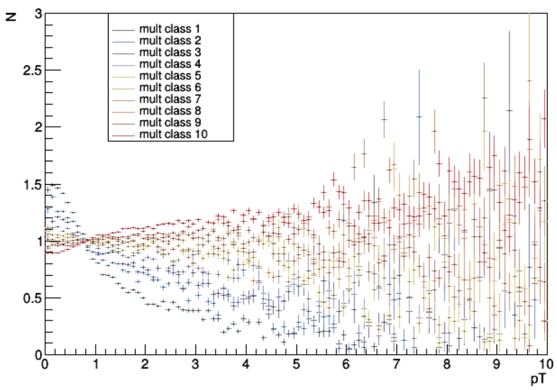


(a) NOCR: Λ spectrum.

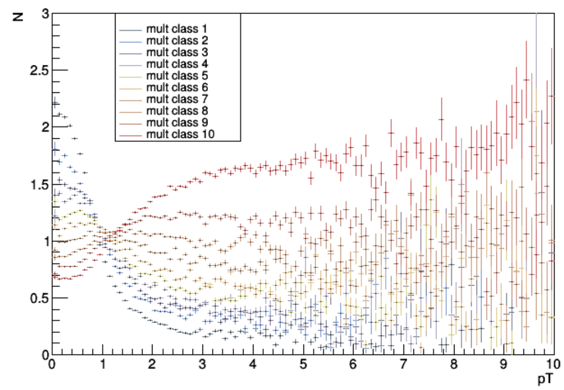


(b) CR: Λ spectrum.

Figure 15: Normalized spectra of Λ.

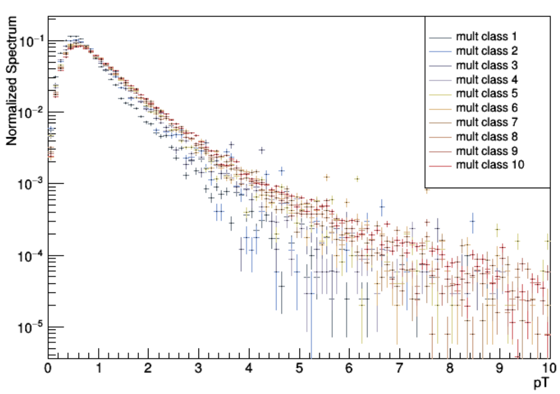


(a) NOCR: Λ minimum bias.

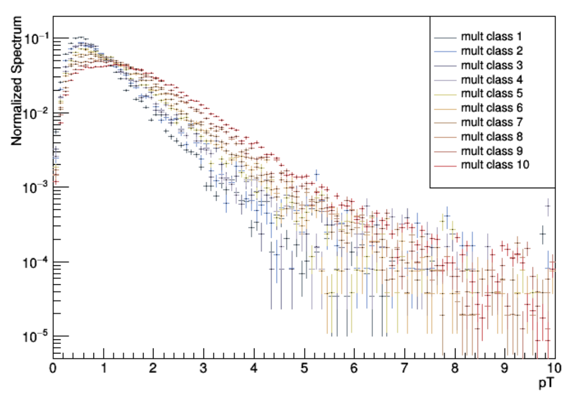


(b) CR: Λ minimum bias.

Figure 16: The minimum bias plots of Λ show the same qualitative effect as the plots above. Above 5 P_t there is a lack of statistics.

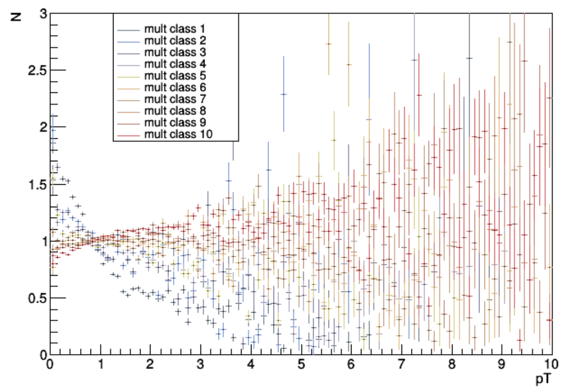


(a) NOCR: Ξ^0 spectrum.

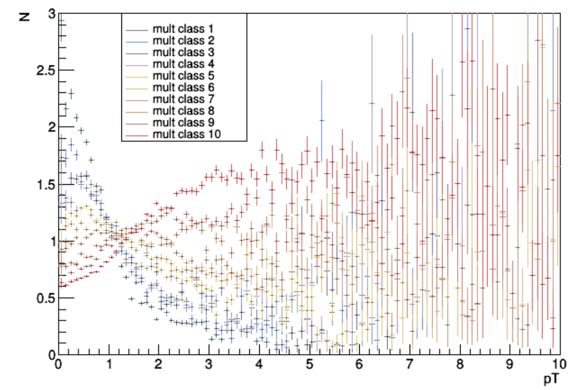


(b) NOCR: Ξ^0 spectrum.

Figure 17: Normalized Ξ^0 spectra.

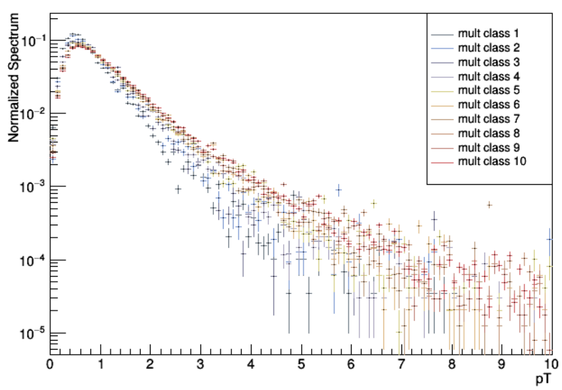


(a) NOCR: Ξ^0 minimum bias.

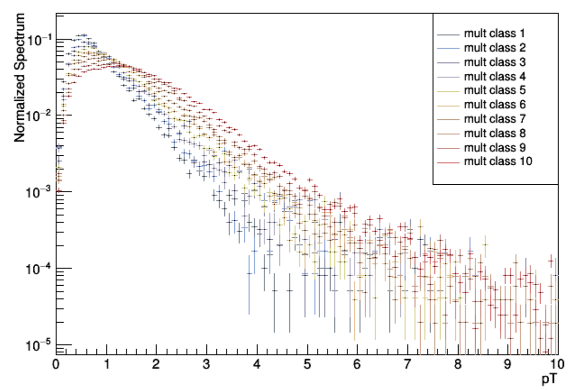


(b) CR: Ξ^0 minimum bias.

Figure 18: Ξ^0 minimum bias plots. The qualitative findings are the same for Ξ^0 as for other particles, above 4 p_{T} there is a lack of statistics.

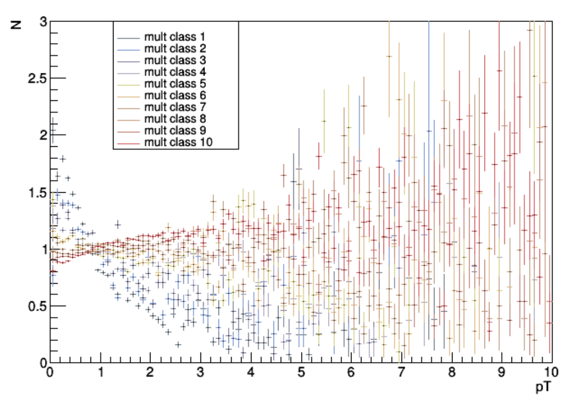


(a) NOCR: Charged $\Xi_{\pm}$ spectrum.

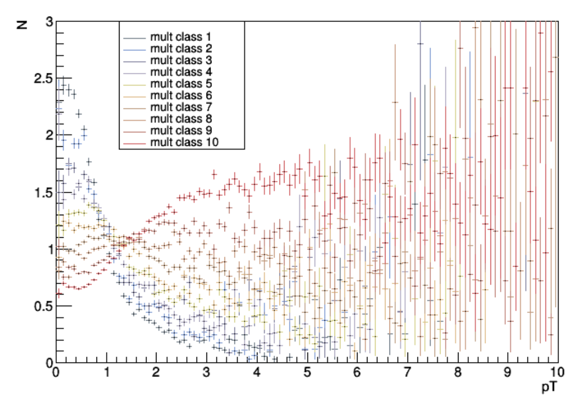


(b) CR: Charged $\Xi_{\pm}$ spectrum.

Figure 19: The plots of the $\Xi_{\pm}$ spectra, show that higher multiplicity values have a harder spectrum. Comparing NOCR (left) to CR (right) for every plot also reveals that this difference between the multiplicity classes is enhanced for CR.



(a) NOCR: Charged $\Xi_{\pm}$ minimum bias.



(b) CR: Charged $\Xi_{\pm}$ minimum bias.

Figure 20: Charged $\Xi_{\pm}$ minimum bias plots. Above $5 < P_t >$ there is a lack of statistics.

4.3 Particle yield divided by pion yield per multiplicity class

This section starts with data from ALICE about the yields of different particles divided by the pion yield. The yield of strange particles -*especially heavy strange particles*- increases with mean multiplicity in this data.

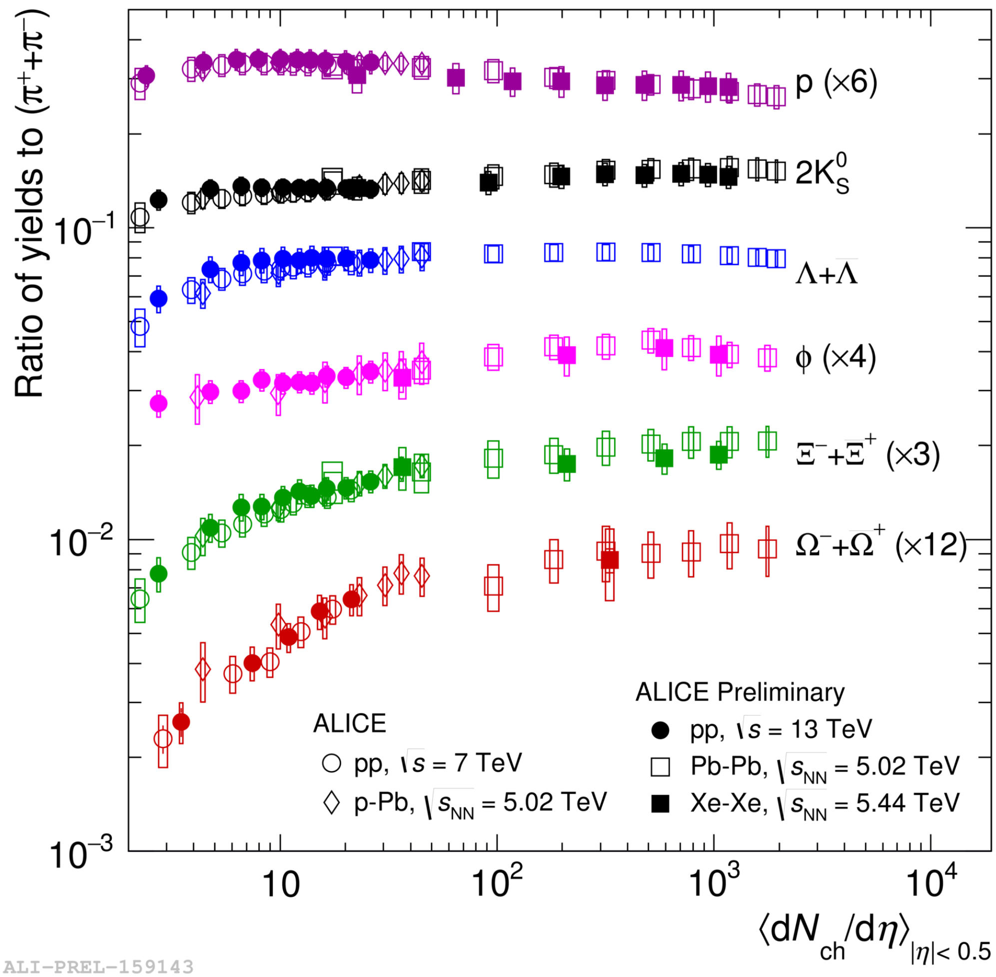


Figure 21: The ALICE values and trends for the yield of target particles divided by the yield of pions. From [2]

The results found by this thesis, Figure 22, differ somewhat from the results found at ALICE Figure 21. For the two lowest multiplicity classes, it appears that there is a relatively high amount of strange production while the ALICE data shows an opposite trend. From multiplicity class 3: $< dN/d\eta >= 5$, the findings are qualitatively in accordance. From that point there is a growing strange production with higher multiplicity class.

In every plot it becomes clear that for every strange particle, the ratio ”strange particle”/”pions” is significantly higher for CR than for NOCR. And the heavier the strange particle becomes, the more pronounced the rise in the ratio of the strange particle's yield to pions becomes. The yield/pion-yield of all the particles can be seen in the Appendix.

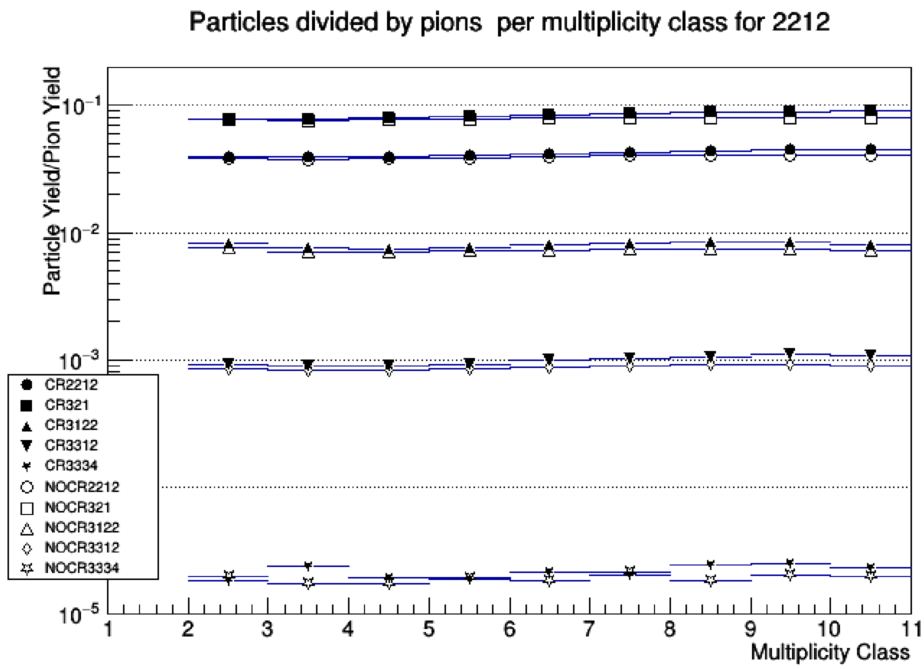
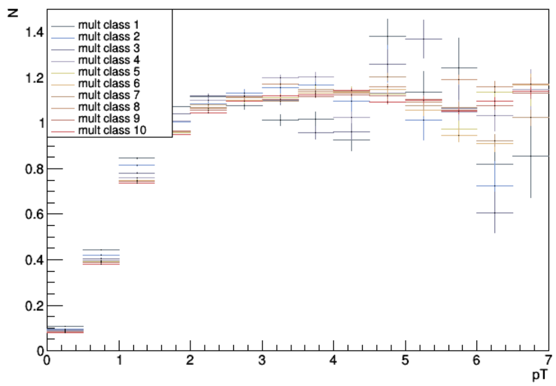


Figure 22: The values of protons, kaons, lambdas, Xis and Omega's divided by pions. It is clearly visible that the CR (black) values are higher than the NOCR (white) values. This trend increases with multiplicity.

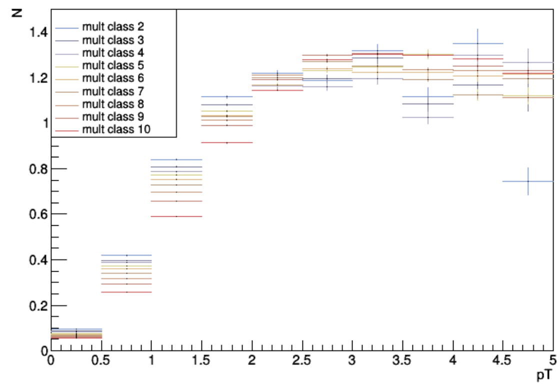
4.4 Spectrum of particles divided by pion spectrum

In this section one sees the spectrum of the "target" particle divided by the pion spectrum for every multiplicity class. The enhanced spread in the multiplicity classes for CR as opposed to NOCR is again very clear from these plots. There is a difference in the plots between the heavier particles and the lighter: The heavier ones have high multiplicity classes that relatively have a higher ratio.

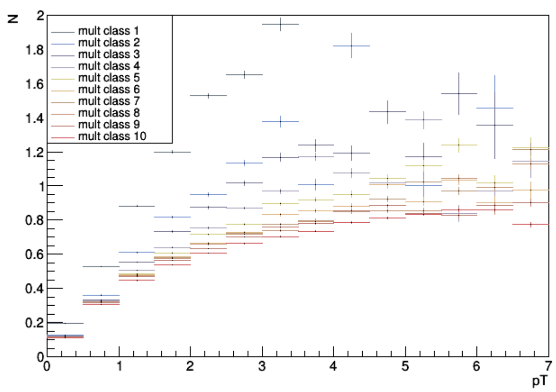
For every ratio-plot there is a rise with p_{T}. This is caused by the fact that heavier particles have a "harder" spectrum relative to pions. Furthermore, the multiplicity dependence of the CR ratio's is more pronounced than the NOCR ratio's. The heavier particles thus exhibit a significantly higher multiplicity dependence than the pion with CR on.



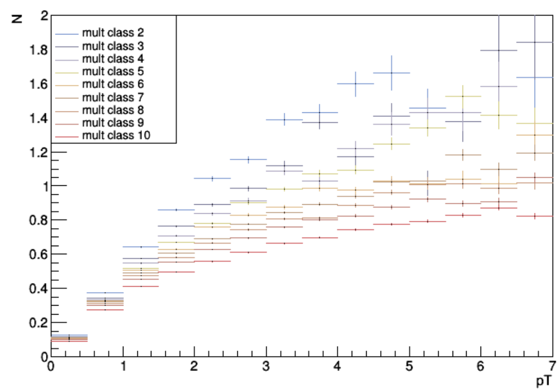
(a) NOCR: Spectrum of protons divided by pions



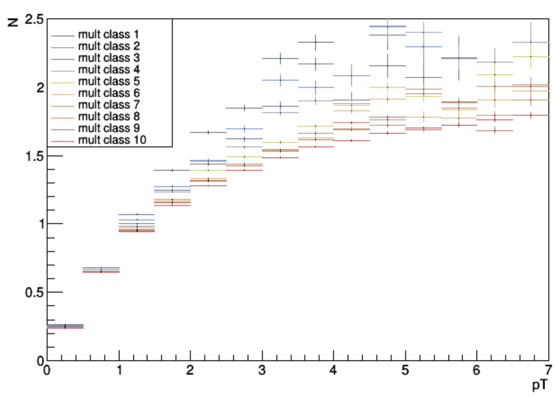
(b) CR: Spectrum of protons divided by pions



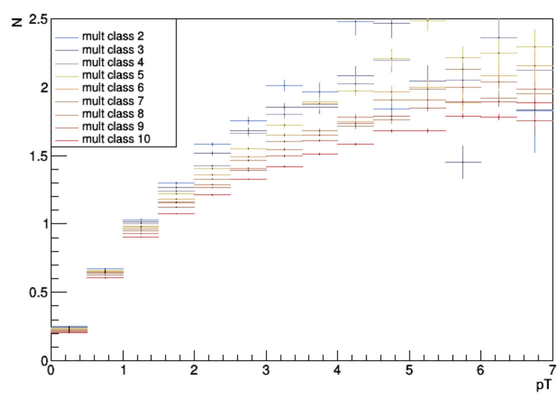
(a) NOCR: Spectrum of K^0_{sh} divided by pions



(b) CR: Spectrum of K^0_{sh} divided by pions

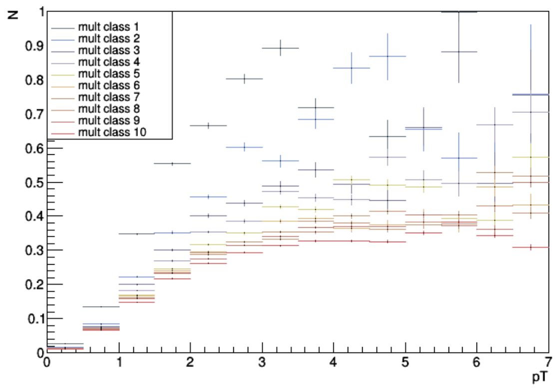


(a) NOCR: Spectrum of $K^{\pm}$ divided by pions

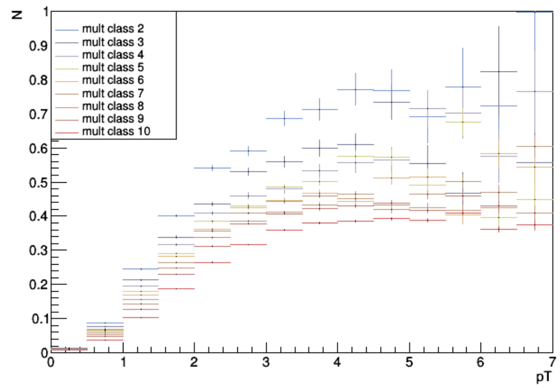


(b) CR: Spectrum of $K^{\pm}$ divided by pions

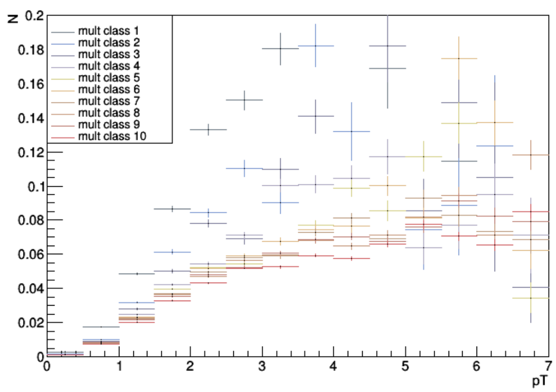
Figure 25: These plots show that the multiplicity dependence of the CR data is more pronounced



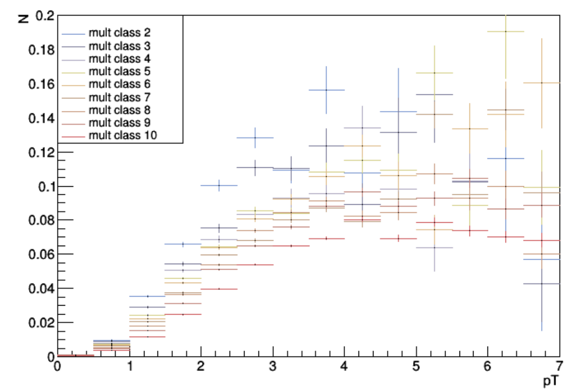
(a) NOCR: Spectrum of Λ divided by pions



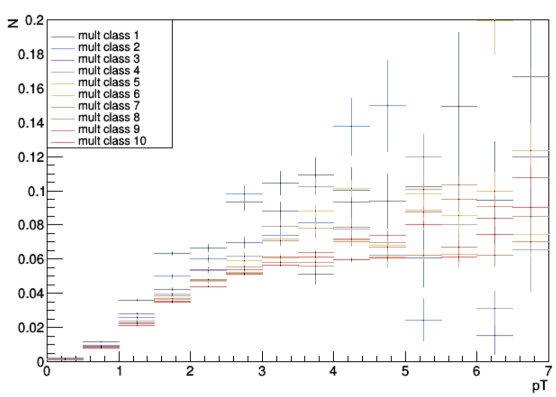
(b) CR: Spectrum of Λ divided by pions



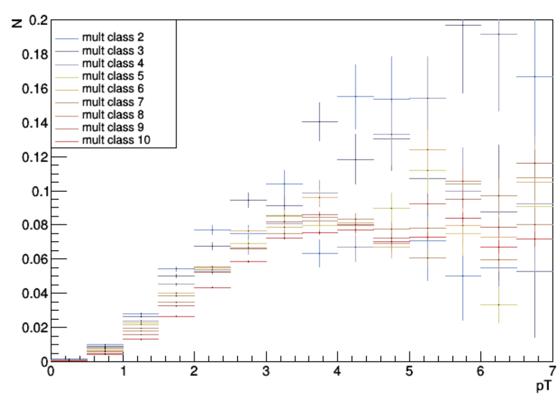
(a) NOCR: Spectrum of Ξ^0 divided by pions



(b) CR: Spectrum of Ξ^0 divided by pions



(a) NOCR: Spectrum of $\Xi^{\pm}$ divided by pions

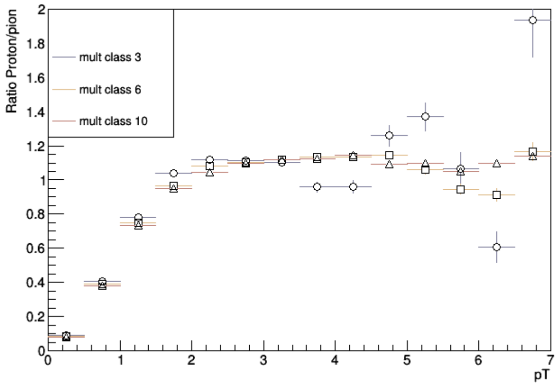


(b) CR: Spectrum of $\Xi^{\pm}$ divided by pions

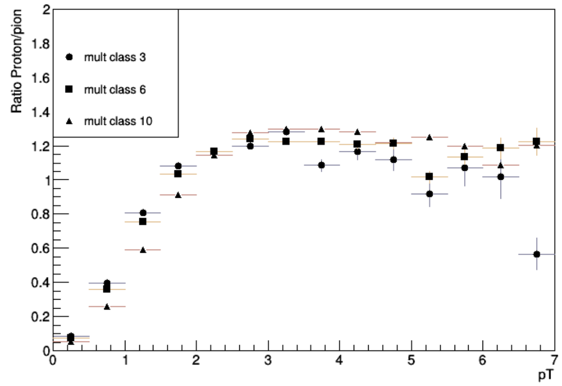
Figure 28: These plots show that the multiplicity dependence of the CR data is more pronounced

4.5 Spectra of p/π and Λ/K_s^0 as a function of multiplicity classes

In this section the baryon over meson ratio for strange particles and non-strange particles is compared. The strange Λ to K_s^0 ratio in this section is also compared to the data from ALICE. The p/π ratio serves as a comparison to the non-strange particles. Comparing 30b

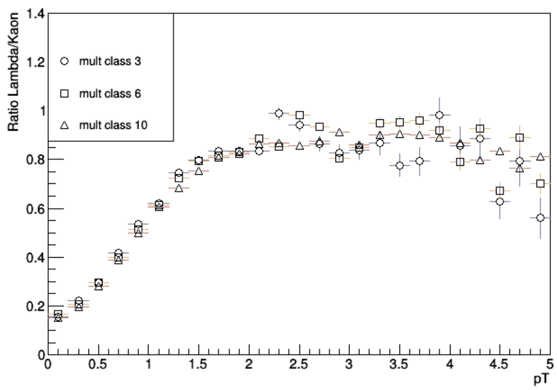


(a) NOCR: Proton spectrum divided by pion spectrum.

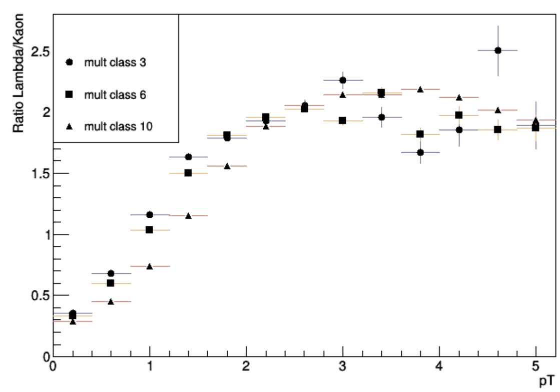


(b) CR: Proton spectrum divided by pion spectrum.

Figure 29



(a) NOCR: Λ spectrum divided by K_s^0 spectrum $\times$ 2.



(b) CR: Λ spectrum divided by K_s^0 spectrum $\times$ 2.

Figure 30: these plots show the division between the Λ spectrum and the K_s^0 spectrum. For CR Higher multiplicity values have a higher ratio, this effect is not seen in the NOCR plot.

and the pp part of 31 shows almost the same properties. The high multiplicity class has a higher "peak" p_T value, and the ratio is also higher at these higher multiplicity values. This is a trend that is also seen in 30b, moreover, this trend is NOT seen in 30a.

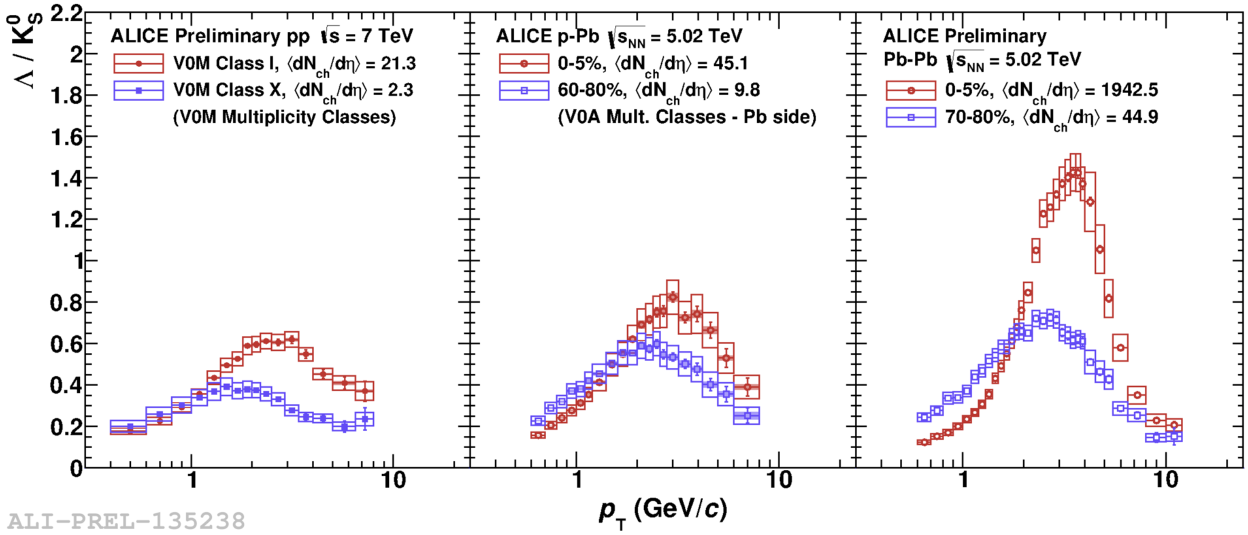


Figure 31: ALICE: Λ spectrum divided by K_s^0 spectrum for pp, p-Pb and Pb-Pb collisions [2]

5 Conclusions

This thesis set out to find an answer to the following questions:

Does Color Reconnection enhance Strange particle production as a function of multiplicity? and *Does Color Reconnection addition to PYTHIA enhance QGP phenomena in rendered pp collision events?*

It was found that Color Reconnection enhances strange particle production and it also seems like Color Reconnection slightly enhances the rate of strange particle production as a function of multiplicity. 22. Thereby, it was found that Color Reconnection increases the mean p_T as a function of multiplicity class 6. Furthermore, the spectra of Λ over K_s^0 30b resemble experimental data from ALICE very well qualitatively. Concluding, this thesis finds qualitative reasons that imply that CR causes many of the phenomena attributed to the formation of a QGP.

6 Discussion and Outlook

Most of the plots shown have only small uncertainties and since the conclusions drawn in this thesis are of a qualitative nature, the results and conclusions are not affected by them.

However, there are some unexpected findings. The first-, second- and third multiplicity classes do not behave as expected when looking at the number of particles divided by the number of pions for every multiplicity class 22. Disregarding those first three classes brings back expected results, but there might be something wrong with the PYTHIA data generation there. One of the possibilities is that this has something to do with the minimum p_T range, which is higher for ALICE than for this thesis.

This research could be refined by analyzing more events. Even though this research analyzes data samples of around 40 million events, there are too few Omega particles created to be able to do qualitative analysis. By performing the same research with 400 million generated events, the Omega data could be better compared against the ALICE data.

References

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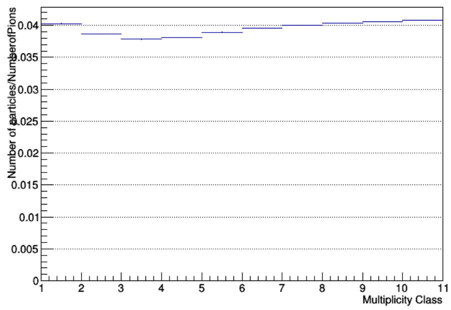
[10] Last visited on 11th of June 2018 URL: `https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png`

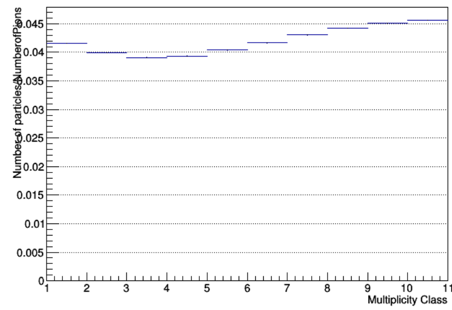
A Appendix

If there is a bulk of material in your thesis, that is not essential for the line of reasoning, but is essential for an indepth understanding of your results, consider postponing it to the end of your thesis in an appendix.

A.1 Yield of particles divided by yield of pions versus multiplicity class

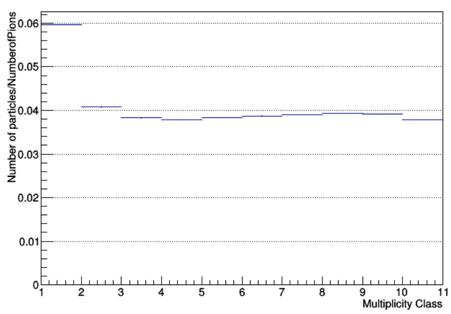


(a) NOCR: p

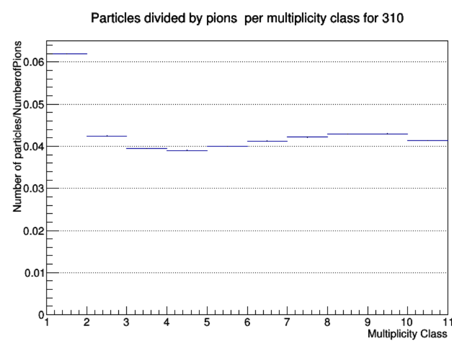


(b) CR: p

Figure 32: The ratio of protons to pions is somewhat higher for CR than for NOCR

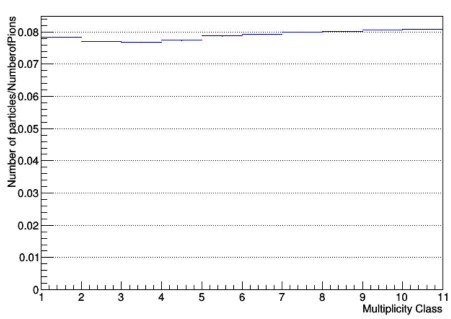


(a) NOCR: K_s^0

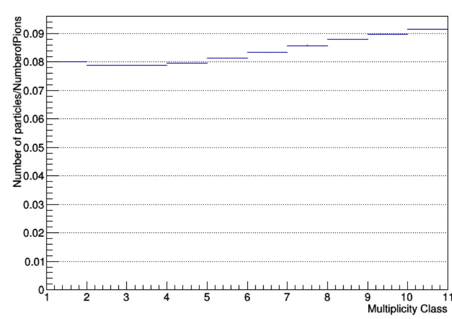


(b) CR: K_s^0

Figure 33: The ratio of K_s^0s to pions is somewhat higher for CR than for NOCR

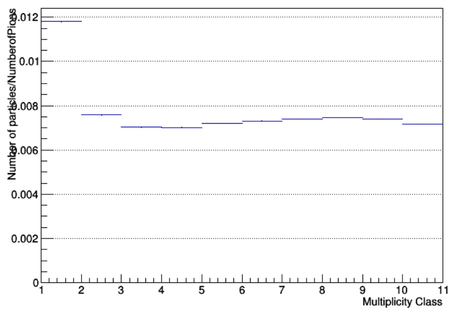


(a) NOCR:$K^{\pm}$

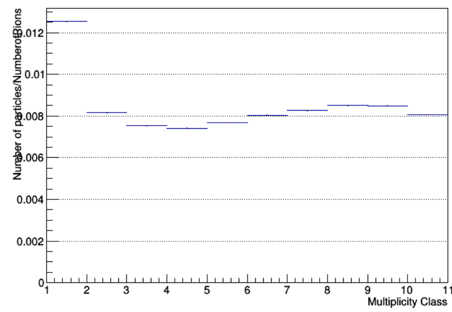


(b) CR:$K^{\pm}$

Figure 34: The ratio of $K^{\pm}$ to pions is somewhat higher for CR than for NOCR, this effect seems to get stronger with higher multiplicity, and the 'angle' also seems to be steeper for CR

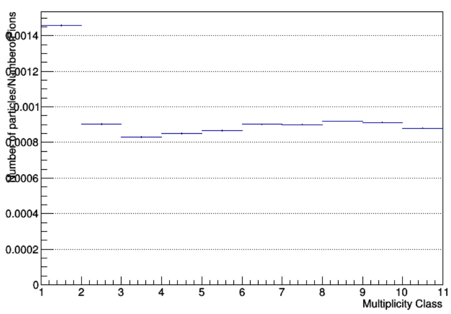


(a) NOCR: Λ

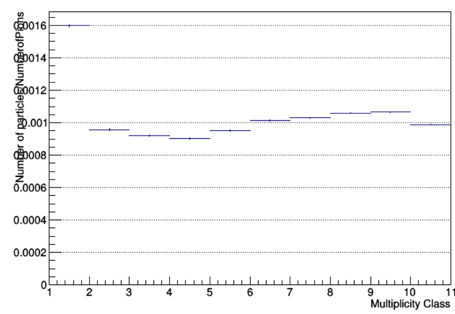


(b) CR: Λ

Figure 35: The ratio between Λ and pions is markedly higher for CR than for NOCR. This might be an indicator for increased strangeness production

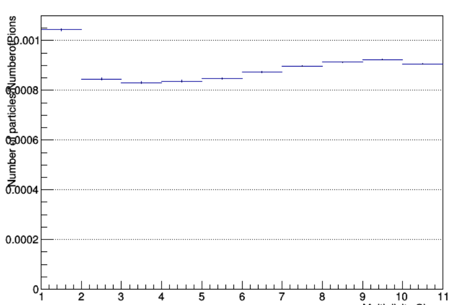


(a) 1b

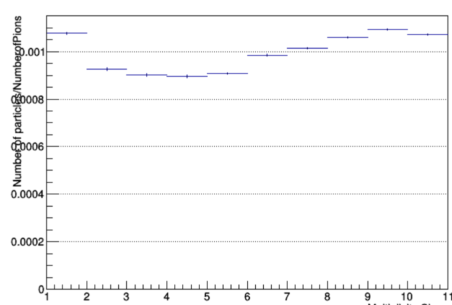


(b) 1b

Figure 36: the ratio between Xi0's and pions is markedly higher for CR than for NOCR. This indicates increased strangeness production

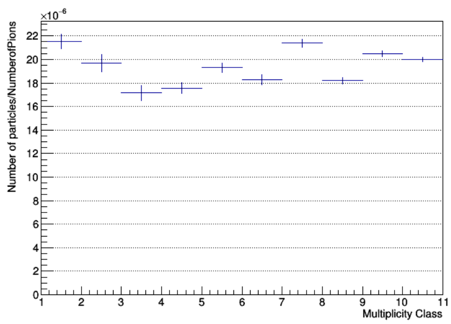


(a) 1a

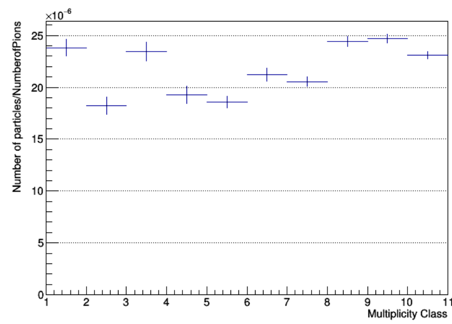


(b) 1a

Figure 37: the ratio between Xi's and pions is markedly higher for CR than for NOCR. This effect increases strrongly for higher multiplicity classes. This indicates increased strangeness production



(a) 1b



(b) 1b

Figure 38: the ratio between Omega's and pions is markedly higher for CR than for NOCR. This indicates increased strangeness production. The errors in these plots are relatively big, but the trend is clear