Universiteit Utrecht

Opleiding Natuur- en Sterrenkunde

Investigation of boosted W bosons in vacuum and the quark-gluon plasma

Bachelor Thesis

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Abstract

Because the W boson has no color charge, it will not be affected by a strongly interacting quark-gluon plasma. This allows us to observe the quark-gluon plasma at different time scales. In this thesis, we try to observe the effects of jet quenching on the quark-antiquark decay particles of a W boson. We use two different simulation programs for this. Pythia8 can simulate hard scattering with weak coupling and Jewel van simulate hard scattering with the creation of QGP. For Pythia8 we plotted the groomed mass and fitted it with a double-sided crystal ball function. Then we plotted the groomed mass for Jewel and compared the two plots. We predict the Jewel plots to have the same double-sided crystal ball function but with a difference in the Gaussian or tail. We found that Pythia8 and Jewel have the same fit however the Jewel plot is thinner and longer in shape.

Contents

1 Introduction

Researchers believe that only 10 microseconds after the Big Bang, the entire universe consisted of a phase state called quark-gluon plasma. Shortly after, the plasma transitioned into hadrons, the building blocks of all matter [1].

Researchers can recreate this quark-gluon plasma using heavy-ion collisions. In particle accelerators, like the Large Hadron Collider in Geneva, beams of particles are accelerated and collided. These collisions are sometimes referred to as "Little Bangs" and can create extremely high temperatures and densities. By closely studying these "Little Bangs" and the quark-gluon plasma properties we can learn a lot about the state of the universe right after it was created [2].

To learn the properties of the quark-gluon plasma we need to look at the effect that the plasma has on particles. During the collisions, sprays of particles are created that have to pass through the plasma. The particles with color charge start to lose energy through strong interactions with the plasma [3]. We can model these collisions and energy losses using simulation programs. We can also control which particles are created during the heavy-ion collisions.

Our interest lies in the production of W bosons during the heavy-ion collisions. W bosons have no color charge so they don't interact with the quark-gluon plasma. Its decay product (quarks) however do interact [4]. By changing the kinematics we can control when the W bosons decay into quarks and how much quark-gluon plasma the decay products traverse.

In this thesis, I study how much and what effect quenching has on the quark-antiquark pair from the W bosons decay that experimentally is observed by reconstructing jets. To understand the effect of jet quenching, we will use 2 different simulation programs. First, we will run a collision using Pythia8, without any jet quenching effect. From here we plot the mass peak and run a double-sided crystal ball fit. For the second run, we use Jewel, a program with quenching programmed into the simulation. We again plot the mass peak and run a fit. We expect that the Jewel plots will also be double-sided crystal ball functions. However, the shape of the Gaussian or the tails may be different than for Pythia8.

2 Theory

2.1 LHC

To better understand the heavy-ion collisions that we model, we first have to understand where the original particle collisions take place. For heavy-ion collision experiments, you need strong accelerators and particle detectors. For this thesis, we will model the collisions as they would happen in the Large Hadron Collider in Geneva.
The Large Hadron Collider (LHC) is the most powerful particle accelerator in the world and accommodates the heavy-ion collisions. It can have collisions of up to 13 TeV, next year 14 TeV.

The beams of particles go through several accelerators to increase their energy until they eventually get injected in a 27 km long ring containing superconducting magnets. The particle beams get accelerated to close to the speed of light while traveling opposite of each other until they eventually collide.
The collisions can happen at four different particle detectors inside the large LHC ring, namely CMS, LHCb, ATLAS, and ALICE depending on the experiment that is being conducted [6]. See Fig. 1 for an illustration of the LHC.

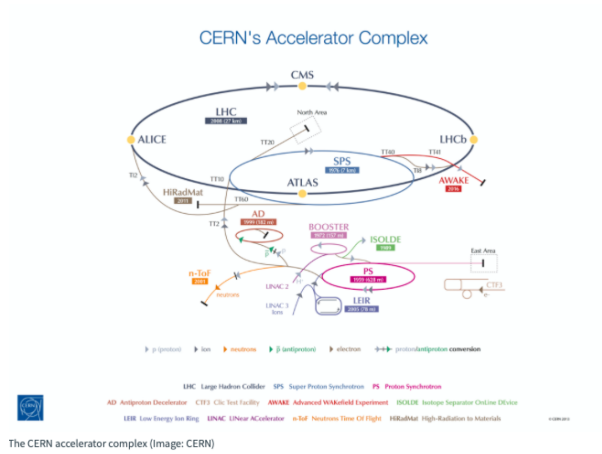


Figure 1: The CERN accelerator complex. Figure adapted from J.Haffner, 2013 (https://home.cern/resources/faqs/facts-and-figures-about-lhc).©CERN,Licence:CC-BY-4.0 [5]

The collisions that are modeled in this thesis happen mainly at the ALICE particle detector. In ALICE the temperatures and energies get so high that particles start to melt and quark-gluon plasma is created, which will be explained in section 2.2 [7]. The ALICE detector consists of multiple layers that can detect different particles.

2.2 QGP

During a lead-lead (Pb-Pb) collision in ALICE, the temperature and density get high enough for quark-gluon plasma to form. This same state of matter was probably present about 10 microseconds after the Big Bang [8].

At room temperature, the strong force confines the gluons and quarks inside particles with no color charge. When the temperature or density get extremely high a property called asymptotic freedom takes place. Asymptotic freedom states that when the energy in a system increase and the distance between particles decreases, the interaction between those particles becomes weaker. This means that the quarks and gluons become deconfined. This phase of matter is called the quark-gluon plasma (QGP) [9, 10].

Before QGP was experimental proven, theoretical physicists predicted QGP to be a gas phase. But experiments concluded that QGP acts like a nearly perfect color liquid [11].

2.3 W Boson

In heavy-ion collisions at the LHC, besides QGP, high energy particles are created in hard scatterings. In this thesis, we focus on the production of two W bosons ($W^{\pm}$).

In the LHC a $W^{\pm}$ is produced by a proton-proton annihilation, where two quarks, one of each proton, interact. This process must occur twice using the same two protons, to end up with two $W^{\pm}$.

After there creation, the $W^{\pm}$ will decay into an quark-antiquark pair, about 75% of the time. Or a lepton-neutrimo pair, about 25% of the time [12]. Those quarks or leptons will continue to decay in a spray of particles. These sprays of particles are called "Jets". In this thesis, we specifically look at the $W^{\pm}$ that decay into quarks [4]. The full creation and decay of the two $W^{\pm}$ can be seen in the Feynman diagram in Fig. 2.

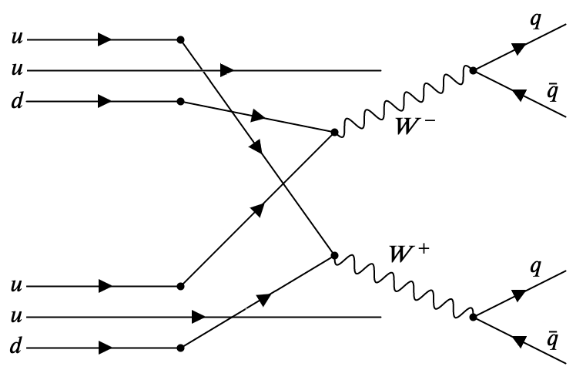
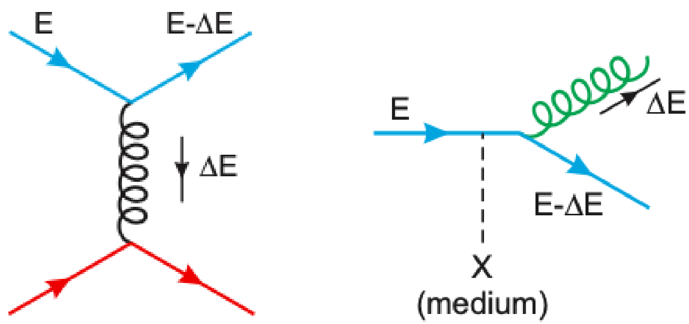


Figure 2: W boson production in a collision between a two protons.

$W^{\pm}$ are particles, that have no color charge. This means that the strong force created by the QGP does not act on the $W^{\pm}$. This is an important property for this thesis because that means that the $W^{\pm}$ won't be affected by the QGP. This gives us a unique chance to observe the QGP plasma at different time scales.. Where the $W^{\pm}$ don't get affected by the QGP plasma, it's decay particles do because quarks have a color charge.

2.4 Jet Quenching



(a) Collisional scattering (b) Radiative scattering

Figure 3: Diagrams for collisional (left) and radiative (right) energy losses of a quark of energy E traversing a quark-gluon medium. Figure adapted from D.d'Enterria, 2009 (https://arxiv.org/abs/0902.2011v2)[3]

After the heavy-ion collision, the quarks that follow from the $W^{\pm}$ decay have to pass through the QGP medium. The quarks interact strongly with the quarks in the medium, which causes energy loss. This energy loss is known as "jet quenching" [3].

The hard quark scattering with partons in the QGP can happen via elastic "Collisional energy loss" or inelastic "Radiative energy loss" interaction.
Collisional energy loss happens when the quark scatters with a quark in the medium and produces again two quarks, now with a different energy. See Fig. 3b.
Radiative energy loss happens when multiple scattering between the quark and the medium induces gluon radiation. The gluon contains both energies form the medium as from the quark [13]. See Fig. 3a.
Both types of quenching can occur and it can occur multiple times. After a while, all partons produced in the shower initiated by the original hard quark will result in a hadronic spray, known as a jet.

3 Methode

3.1 Simulations

To get a clear picture of the effect of jet quenching, we will compare the generated event of two simulation programs. We look at Pythia8 and Jewel. The events from these simulation programs are clustered by the FastJet package into the right jets. After this, we use JetToyHI to calculate necessary observables and we collect these observables in a JetTree file. In addition to this process, we use Root to analyze our data, which gives us the results.

3.1.1 Pythia8

Pythia8 is a program that simulates high-energy collisions as they would take place in ALICE. From the simulation, events can be generated by passing through three levels. The first level is choosing a process, the process we are looking at is a weak interaction where two $W^{\pm}$ are created. In the second level, the parton configuration associated with the previous process is generated. In the third level, Pythia8 uses the laws of physics to simulate the interactions between particles and the decay of unstable particles. The final particles from this process, together form the event and are stored in a pu14 file [14].

In this process, several parameters need to be filled. The parameters used for this thesis are the following; the number of events is set at 10000, and the tune is set to 14. Our collision is hard scattering according to QCD with weak coupling. The collision takes place in a vacuum. The last parameter is the $\hat{P}t$ that changes the Pt value of the initial $W^{\pm}$. In this thesis, we look at four different $\hat{P}t$ in the values of 120, 220, 320, 520, and 670. These values are taken high on purpose, so that the angle between the quarks, which decay from the $W^{\pm}$, is very small.

The information from the events stored in the pu14 files only contains the final particles and partons and no information about their origin from a jet. We use FastJet to cluster the particles closest to each other to find the jet structure. At a high $\hat{P}t$, instead of two single jets, FastJet will reconstruct a combined jet [15].

In addition to the original reconstructed jet, we also receive the information from a groomed jet. This grooming is done with the help of FastJet SoftDrop. Soft Drop uses two techniques to remove background information. The first technique removes the particles at a wide-angle from a jet. The second technique compares the variables of two particles to find the background. After the Soft Drop, you are left with a jet with a large part of the background removed. As before, a high $\hat{P}t$ gives combined groomed jets [16].

With the information we retrieved from Pythia8 and FastJet, JetToyHI can calculate the required observables. These observables are stored in a JetTree file, from which we can retrieve the information when necessary [17].

3.1.2 JEWEL

Jewel is a program that simulates high-energy lead0lead collisions. Jewel relies heavily on Pythia to simulate the beginning parton showers, and for the hadronization that takes place at the end of the simulation. Jewel itself adds the physical laws that describe a particle when as it passes through quark-gluon plasma. This gives you a heavy-ion collision simulation that works similar to the simulations of Pythia but with the effects of jet quenching added [18]. For Jewel, we work with 3910 events and a $\hat{P}t$ of 10. Jewel also utilizes event weight. This means that every event has a certain weight that tells you how many times that event counts. Because of this, you need to add the event weight when you fill the plot.

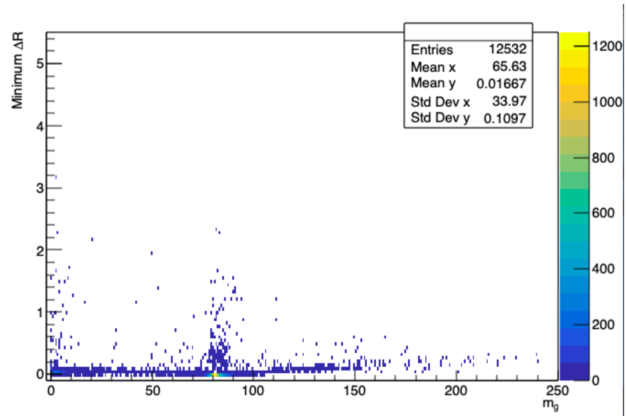
3.2 Extraction of W boson signal

This thesis aims to observe the effect of jet quenching on the quark-antiquark pair from the W bosons decay that experimentally is observed by reconstructing jets. To achieve this goal, the groomed mass is plotted and fitted. When plotting the groomed mass, for Pythia8, with a log scale on the y-ax, it became clear that the graph was not a perfect Gauss. There was a clear tail on both sides similar to a $\frac{1}{x}$ function. This showed that we needed a function of a Gauss with two power-law tails. The fit we use for this is a crystal ball function with a power-law tail on both sides. See Eq. 1 in Appendix A for the full function.

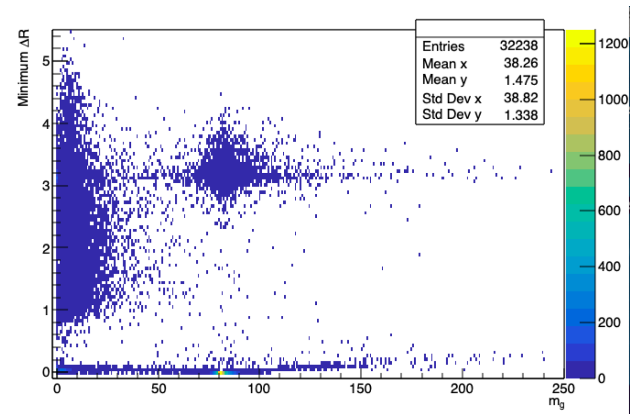
After the Pythia8 groomed mass plot is correctly fitted we start to look at the Jewel events. The groomed mass plot from Jewel and Pythia8 need to be compared, but they have a different $\hat{Pt}$ value, and a different amount of events. To make sure we can compare the two we need to make sure that the two plots run over the same jet Pt value. When we look at a Pythia8 plot with $\hat{Pt}$=120, we need both Pythia8 and Jewel to only plot the jets with jet Pt=130 or higher. A second thing that needs to be done is to get both plots normalized and rebined, putting four bins in one. After these steps, we can compare the two plot by combining in the same graph.

3.3 Quality assurance

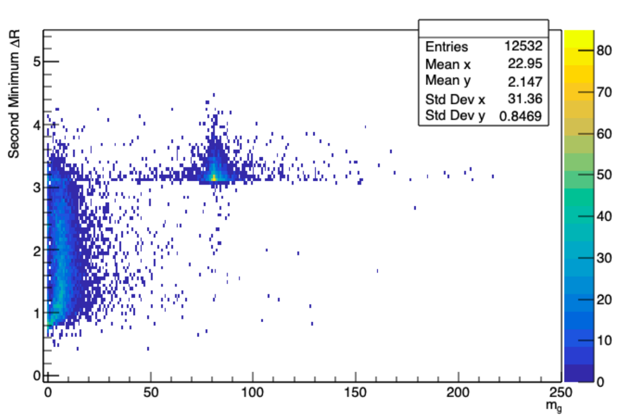
Before we started comparing the Jewel and Pythia groomed mass plots we first needed to make some quality assessments. Because Pythia gives us both information on a parton level and a groomed jet level, we can assess when you are dealing with an actual $W^{\pm}$. For this, we use ΔR, which can tell us when 2 jets are the same. Say you take a $W^{\pm}$ groomed jet and a $W^{\pm}$ on parton level, when ΔR <0.1 you can safely say that you are looking at the same $W^{\pm}$ jet.



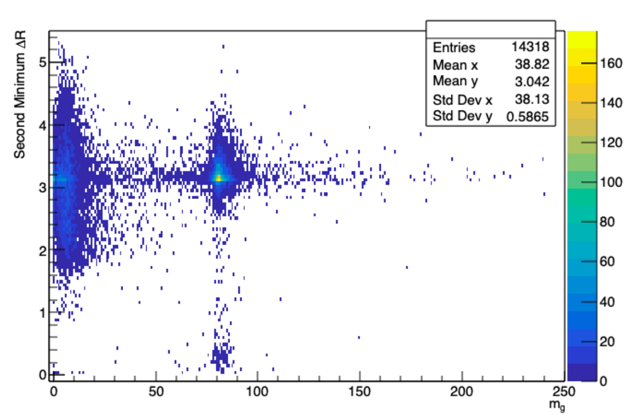
(a) Minimum ΔR matching partons $W^{\pm}$ to groomed jets $W^{\pm}$.



(b) Minimum ΔR matching groomed jets $W^{\pm}$ to partons $W^{\pm}$.



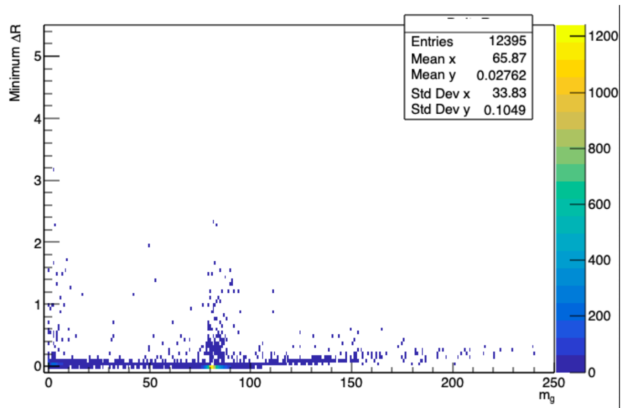
(c) Second minimum ΔR matching partons $W^{\pm}$ to groomed jets $W^{\pm}$.



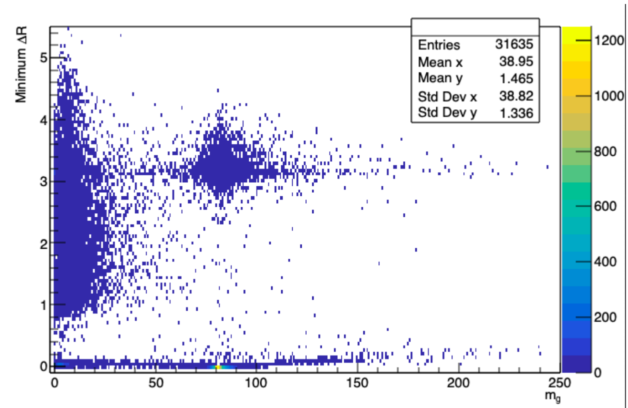
(d) Second minimum ΔR matching groomed jets $W^{\pm}$ to partons $W^{\pm}$.

Figure 4: The minimum ΔR and second minimum ΔR plotted for two different loops. All with a R=0.8 and a $\hat{P}t = 320$.

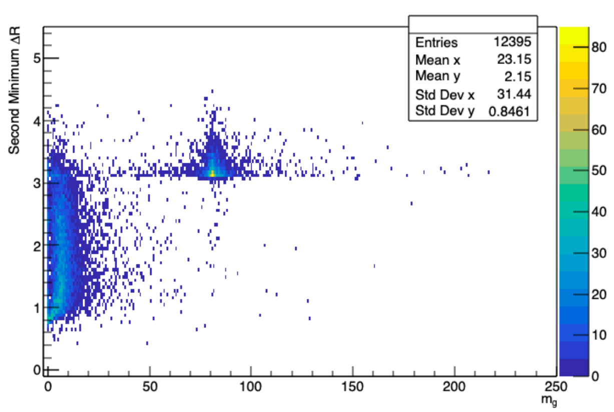
In Fig. 4 we have plotted the minimum ΔR against the groomed mass within two different loops. The first loop took the $W^{\pm}$ on parton level and then took the groomed jets that matched those $W^{\pm}$, as seen in Fig. **??** and Fig. 4c. The second loop took the groomed jets related to the $W^{\pm}$ and then matched the $W^{\pm}$ on parton level, as seen in Fig. 4b and Fig. 4d We did this again for the second minimum ΔR.
We found out that for the second loop there was a group of jets around groomed mass 80 and minimum $\Delta R = \pi$. These jets correspond to events where there are two $W^{\pm}$ on parton level, but only one $W^{\pm}$ for the groomed jets. Because of this, the loop matched the other $W^{\pm}$ to a wrong groomed jet.



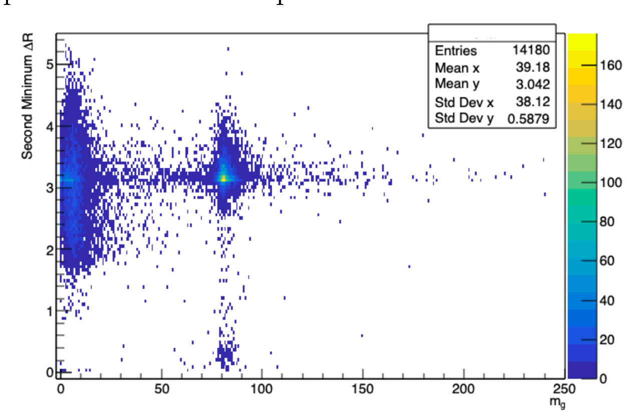
(a) Minimum ΔR matching partons $W^{\pm}$ to groomed jets $W^{\pm}$. With leptons removed.



(b) Minimum ΔR matching groomed jets $W^{\pm}$ to partons $W^{\pm}$. With leptons removed.



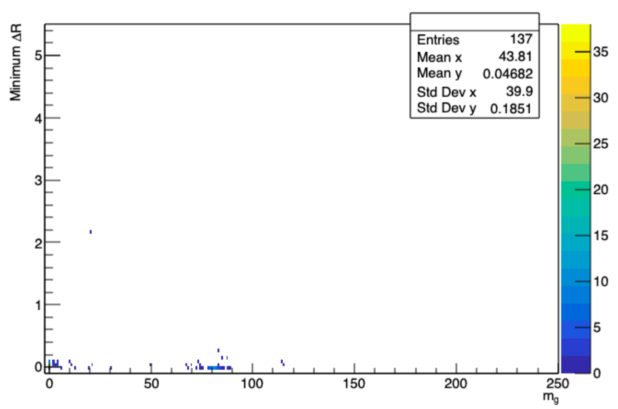
(c) Second minimum ΔR matching partons $W^{\pm}$ to groomed jets $W^{\pm}$. With leptons removed.



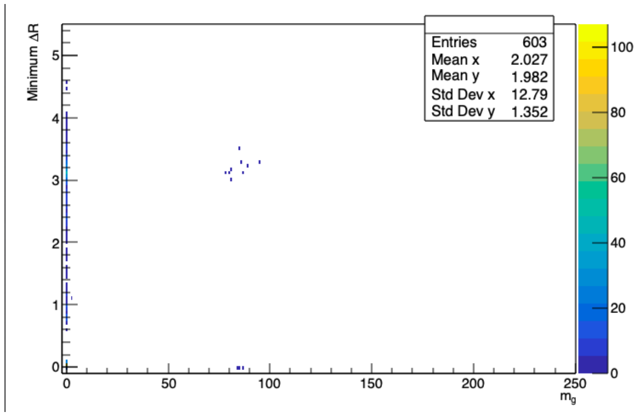
(d) Second minimum ΔR matching groomed jets $W^{\pm}$ to partons $W^{\pm}$. With leptons removed.

Figure 5: The minimum ΔR and second minimum ΔR plotted for two different loops. The jets that decay into leptons have been removed. All with a R=0.8 and a $\hat{P}t = 320$.

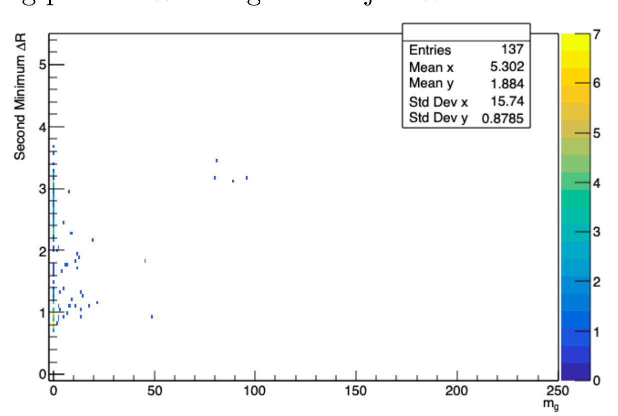
We tried to filter out the jets where the $W^{\pm}$ decays into two leptons instead of two quarks, but that did not affect, see Fig. 5. When we plot only the jets that where removed with this lepton filter we saw that there where only a few $W^{\pm}$ that decay into leptons. See Fig. 6.



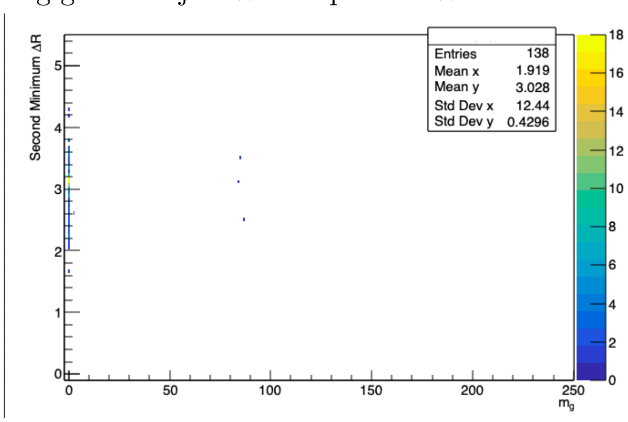
(a) The removed leptons for minimum ΔR matching partons $W^{\pm}$ to groomed jets $W^{\pm}$.



(b) The removed leptons for minimum ΔR matching groomed jets $W^{\pm}$ to partons $W^{\pm}$.



(c) The removed leptons for second minimum ΔR matching partons $W^{\pm}$ to groomed jets $W^{\pm}$.



(d) The removed leptons for second minimum ΔR matching groomed jets $W^{\pm}$ to partons $W^{\pm}$.

Figure 6: The jet that decay into leptons.This is for the minimum ΔR and second minimum ΔR plotted for two different loops. All with a R=0.8 and a $\hat{P}t = 320$.

It still isn't clear why some $W^{\pm}$ are missing, however a large procent of the parton $W^{\pm}$ can be matched to the groomed mass $W^{\pm}$.

4 Results

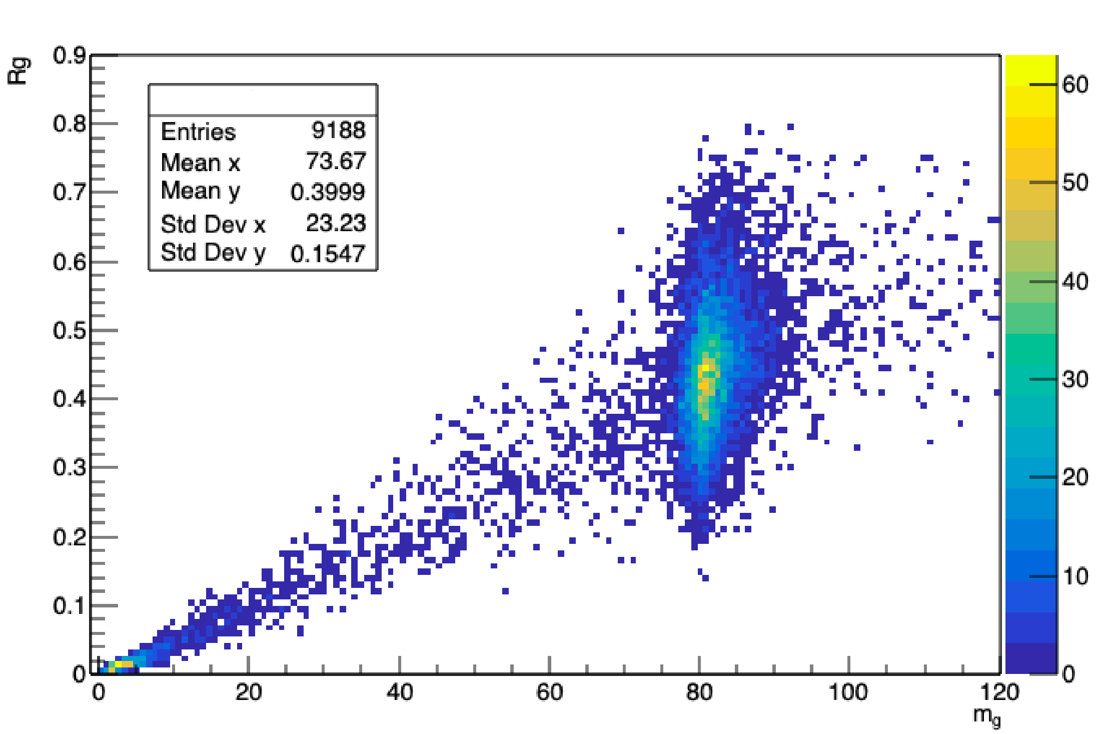
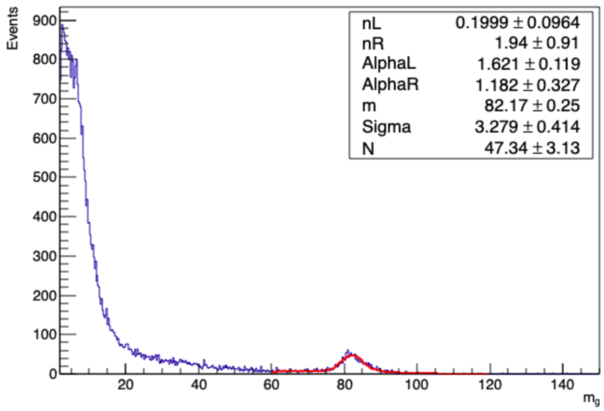
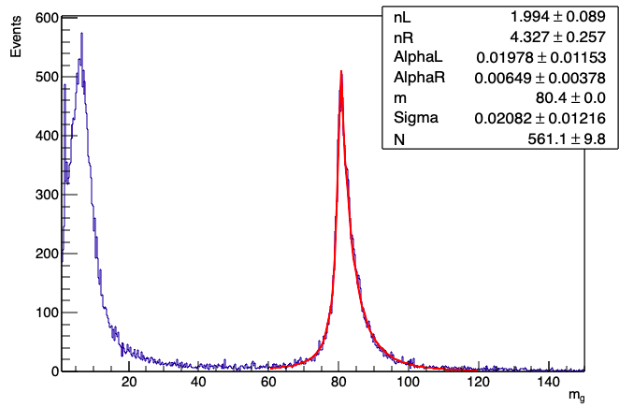


Figure 7: Correlation between the groomed mass and the angle between the subjets for R=0.8. This is with the groomed mass that has a ΔR<0.1.

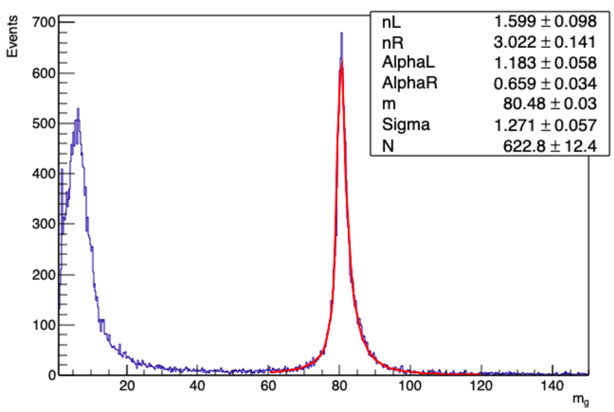
Before we analyze the difference between Pythia8 en Jewel, we first need to assure that the combined jets originate from $W^{\pm}$. Fig. 7 consists of a 2D plot with groomed mass in the x-axis, and Rg on the y-axis. One can see that a large part of the combined jets has a groomed mass of around 80, which is the mass of a $W^{\pm}$. One can also see that those jets have an Rg of 0.4. So the angle between the two sub-jets is quite large, which is characteristic for $W^{\pm}$.



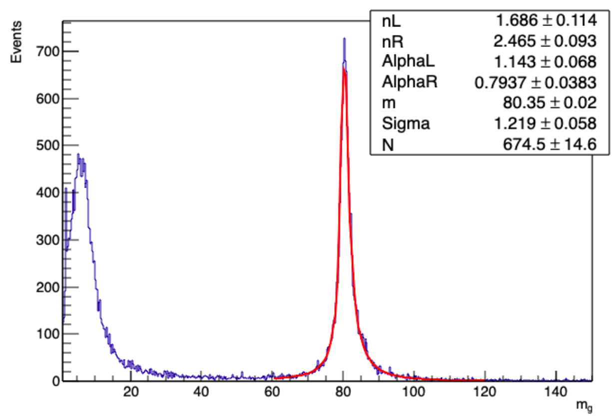
(a) The groomed mass fit for a $\hat{P}t$ of 120.



(b) The groomed mass fit for a $\hat{P}t$ of 320.



(c) The groomed mass fit for a $\hat{P}t$ of 520.



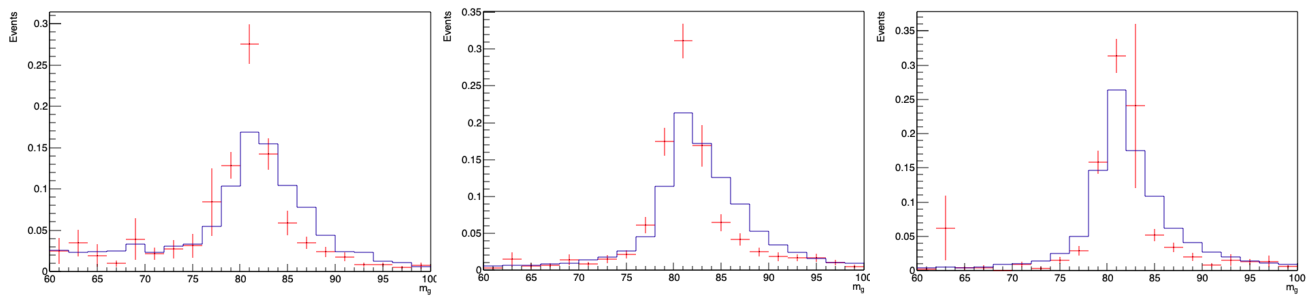
(d) The groomed mass fit for a $\hat{P}t$ of 670.

Figure 8: The groomed mass peaks for R=0.8 and 4 different . The plot is fitted with a double-sided crystal ball function.

Fig. 8 shows the groomed mass distributions with their corresponding fits. One can see that all four plots have a general Gaussian shape but with an abnormality at the tail. The correct fit ends up being a crystal ball function with a double-sided power-law tail. For clarity, the function used for this fit can be found in Appendix A.

The parameters n and Alpha define the power-law fit at the tail of the plot. Because we have a double power-law we need to define the parameters for the left tail (nL and AlphaL) and the right tail (nR and Alpha) separately. These parameters have a wide range. The parameters m and σ on the other hand should have a more defined range. Like you can see from Fig. 8 the parameter m stays around the value of 80, with a small deviation for Fig. 8a. For the parameter σ it is more difficult to see a defined range. From Fig. 8c and Fig. 8d you can state that it sits around a value of 1.2. But Fig. 8a and Fig. 8b both highly deviate from that value. This could be because is here not the standard deviation of the peak but a parameter that connects the two power laws.

One can see that the peaks of the plots have different heights depending on the value of .



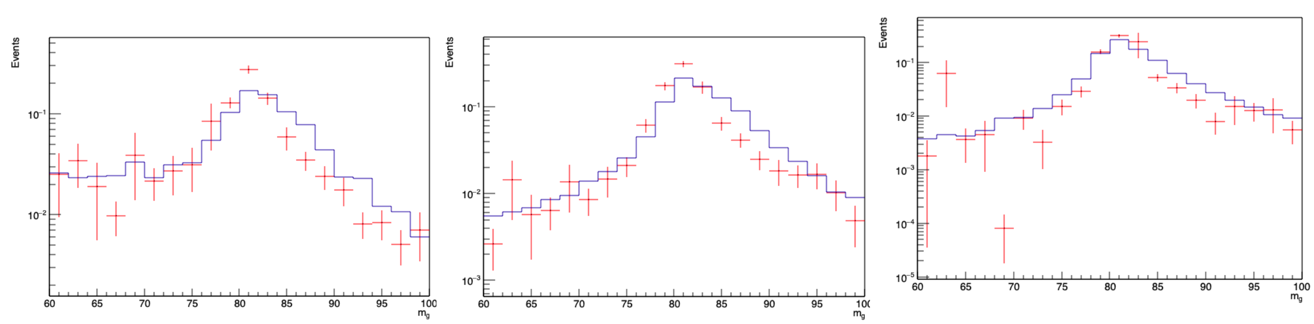
(a) The groomed mass plots of Jewel and Pythia8 for jet Pt>130.

(b) The groomed mass plots of Jewel and Pythia8 for jet Pt>230

(c) The groomed mass plots of Jewel and Pythia8 for jet Pt>330

Figure 9: Normalized Jewel and Pythia8 groomed mass plot for different jet Pt values. All have R=0.8.

Fig. 9 shows the normalized groomed mass plots of Jewel and Pythia8 plotted in the same graph. Because Pythia8 has more events than Jewel, which has only 3910 events, both plots have been normalized. They were also rebined, with four bins put into one. This was all done to make sure that we can compare the two plots with each other. One can see that the Jewel plot has a thinner and higher peak for all three graphs. The tail also seems to be lower at Jewel, but this is perhaps easier to see in Fig. 10.



(a) The groomed mass plots of Jewel and Pythia8 for jet Pt>130 with a logarithmic log-axis.

(b) The groomed mass plots of Jewel and Pythia8 for jet Pt>230 with a logarithmic log-axis.

(c) The groomed mass plots of Jewel and Pythia8 for jet Pt>330 with a logarithmic log-axis.

Figure 10: Normalized Jewel and Pythia8 groomed mass plot for different jet Pt values with a logarithmic y-axis. All have R=0.8.

Fig. 10 shows the same plots as in Fig. 9 but then with a logarithmic y-axis. This gives a better idea of the tails from the Pythia8 and Jewel plots. One can now see that Jewel indeed a lower tail compared to Pyhtia8. It also shows that the right tail has decreased more compared to the left tail.

	Pythia8	JEWEL
Jet m_g >130	7,77215	7,0921
Jet m_g >230	5,97704	5,57059
Jet m_g >330	5,47406	6,39711

Table 1: Table to test captions and labels

When we calculate the width of the mass peaks for both Pyhtia8 and Jewel we see something unusual. For the jet Pt values of 130 and 230, the Jewel peak width is smaller than the Pythia8 peak width. However, for jet Pt 330 the Jewel peak width is larger than that of Pythia8, see Table 1. This stange because Fig. 10c the peak op Jewel seems smaller.

5 Conclusion

In this thesis, we compared the groomed mass plot for two different simulations. One came from Pythia8 with hard scattering and weak coupling. The other came from Jewel with hard scattering and jet quenching because of the presence of QGP. For the Pythia8 events, we found that the best fit for the groomed mass plots was a double-sided crystal ball function. We also found out that the peak hight changes when you use a different $\hat{P}t$. This is because, when you use a low $\hat{P}t$ value, a lot of $W^{\pm}$ may lay outside of the range you are looking at. So only a small amount of jets are put into the plot. When the value of $\hat{P}t$ gets higher your range gets bigger, and more jets are put into the plot.

With this knowledge, we hypothesized that the groomed mass plot from Jewel would also be a double-sided crystal ball function. But we anticipated that the shape of the Gaussian or the power-laws, or the position of the peak on the x-axis, would be different compared to Pythia8.

By comparing the normalized groomed mass plots of Jewel and Pythia8, we found that the Jewel plots are double crystal ball functions. However, quenching makes the plot longer and thinner compared to Pythia8.

6 Discussion

We tried to see the effect that jet quenching has on the quark-antiquark pair from the W bosons decay that experimentally is observed by reconstructing jets. For this, we look at the events of Pythia8, a simulation program with no QGP, and Jewel, a simulation program with QGP. Before we compared the two program's we made a hypothesis. We thought* that the Jewel would be a double-sided crystal ball function just like Pythia8, but the plot would change through quenching. We thought it would either change the Gaussian or power-law, or it would shift the position of the peak on the x-axis. We found that this hypothesis was mostly correct. From the comparison plot, we could see that the plot from Jewel was narrower at the tail of the plot, and the peak was higher. However, when we calculated the

width of the groomed mass plots we found that for a $\hat{P}t$ of 320, the Jewel peak was wider. The reason for this is not clear. It may be a fault in the creation of the events, which would mean that it would be gone if you created new events. But if that is not the case, then we might need to do more research into this.
We also observed that the right tail (the right power-law) had changed more than the left tail. This is because the jets with a higher mass have more particles in the jet. So it has a bigger chance to react with the medium, and therefore lose more mass.

During this thesis, we found some inconsistencies in our plots. We plotted the groomed mass against the minimum ΔR within two different loops. For the second loop, there is a group of jets around groomed mass 80 and minimum $\Delta R = \pi$. These jets correspond to events where there are two $W^{\pm}$ on parton level, but only one $W^{\pm}$ for the groomed jets. Because of this, the loop matched the other $W^{\pm}$ to a wrong groomed jet. We suspected that the missing $W^{\pm}$ in the groomed jets correlated to the $W^{\pm}$ that decay into leptons instead of quarks. Because we are only interested in the quarks we removed the jets that decay in leptons from the minimum ΔR plot. However, the amount of jets that got removed was so small that it could not explain the missing $W^{\pm}$. It has to be noted that the Tau leptons decay very fast into hadrons. So the jets that decay into Tau leptons aren't removed. But because 1/3 of the jets decay into Tau, it would barely make a difference.

6.1 Outlook

So far the interactions between $W^{\pm}$ and QGP have only been researched by simulations. Real data has not been used yet. Currently, the LHC is under a shutdown until February 2021. But in the next 10 years, it will have 2 large run periods [19]. The interaction research between the $W^{\pm}$ and QGP should be one of these upcoming experiments. It would be an interesting follow-up research to plot the same plots as in this thesis but then with actual data and compare the two. Another important follow-up research would be looking into the missing $W^{\pm}$ in the groomed jets. It would be interesting to see what causes this problem and to see if it only occurs when working with $W^{\pm}$.

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A Appendix

The double-sided crystal ball function is a Gaussian with two power-laws, one on each tail. The parameters; n_L, n_R, $Alpha_L$, and $Alpha_R$ control the power-law on the left and right side. The parameter m controls the position of the peak on the x-axis and N controls the height of the peak. The last parameter σ connects the two power laws.

$$f = N \begin{cases} \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \mathrm{e}^{-\frac{|\alpha_L|^2}{2}} \left(\frac{n_L}{|\alpha_L|} - |\alpha_L| - \frac{x-\bar{x}}{\sigma}\right)^{-n_L} & \text{for } \frac{x-\bar{x}}{\sigma} < -|\alpha_L| \\ \mathrm{e}^{-\frac{(x-\bar{x})^2}{2\sigma^2}} & \text{for } -|\alpha_L| \leq \frac{x-\bar{x}}{\sigma} \geq |\alpha_R| \\ \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} \mathrm{e}^{-\frac{|\alpha_R|^2}{2}} \left(\frac{n_R}{|\alpha_R|} - |\alpha_R| + \frac{x-\bar{x}}{\sigma}\right)^{-n_R} & \text{for } \frac{x-\bar{x}}{\sigma} > |\alpha_R| \end{cases} \tag{1}$$