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Charmonia Production within Jets at the LHC

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Abstract

Charmonia are important particles to study QCD and the properties of the quark-gluon plasma. This work will simulate pp collisions at a centre of mass energy of 13 TeV with PYTHIA 8.2 and compare the directions of Charmonia and Jets of different transverse momenta. The Jets get clustered with the anti- k_t algorithm, using FastJet 3.3.3. The goal is to make predictions that can later be tested at the ALICE experiment to gain insight in potential short comings of the models used by PYTHIA for Charmonium production. While the results suffer from a lack of statistics, it was observed that the distance-correlation gets stronger with increasing transverse momenta of both the Jets and the Charmonia.

Declaration of Academic Integrity

I, *Simon Thiele*, hereby confirm that this thesis on "Charmonia Production within Jets at the LHC" is solely my own work and that I have used no sources or aids other than the ones stated. All passages in my thesis for which other sources, including electronic media, have been used, be it direct quotes or content references, have been acknowledged as such and the sources cited.

Münster, November 3, 2020

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I agree to have my thesis checked in order to rule out potential similarities with other works and to have my thesis stored in a database for this purpose.

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1 Introduction

Charmonium is a bound state of a charm and an anti-charm quark ($c\bar{c}$). Its similarity to Positronium, the bound state of an electron and a positron and the fact that it is governed by the strong rather than the electromagnetic force makes Charmonium a good exemplar to study the strong force.[Vol08] So it is important to understand the production mechanisms for Charmonia. "Heavy-flavour hadrons, containing open or hidden charm and beauty flavour, are among the most important tools for the study of Quantum Chromodynamics (QCD) in high energy hadronic collisions, from the production mechanisms in proton–proton collisions (pp) and their modification in proton–nucleus collisions (p–A) to the investigation of the properties of the hot and dense strongly interacting Quark– Gluon Plasma (QGP) in nucleus–nucleus collisions (AA)."[And+16]

Jets are collimated sprays of hadrons that are produced in strong interaction processes in hadronic collisions. Therefore Jets are a good tool to look at the structure of an event. There are different algorithms to cluster the particles of an event into Jets. An important quality of Jet algorithms is Infrared-Collinear safety (IRC safety). IRC safety "is the property that if one modifies an event by a collinear splitting or the addition of a soft emission, the set of hard Jets that are found in the event should remain unchanged." [Sal10] IRC safety is important for several reasons, the main one being that "Collinear splittings and soft emissions effectively occur randomly and even their average properties are hard to predict because of the way they involve non-perturbative effects. [While t]he motivation for constructing Jets is precisely that one wants to establish a way of viewing events that is insensitive to all these effects." However most of the early algorithms, including the first one, fall into the category of iterative cone (IC) or fixed cone (FC) algorithms that are typically not IRC safe. [Sal10] The four main algorithms that are IRC safe are the k_t , Cambridge/Aachen (C/A), anti- k_t and SISCone algorithm. More details on all of them, as well as IRC unsafe algorithms and more information on the usage of Jets can be found in [Sal10]. This work uses the anti- k_t algorithm. The anti- k_t algorithm is a "natural, fast, infrared and collinear safe replacement" [CS08] for the older IRC unsafe Cone algorithms that are typically used at hadron collider experiments [Sal10]. The algorithm itself as well as an example clustering of an event with the four IRC safe algorithms mentioned above can also be found in section 3.3.

The aim of this work is to describe the correlation between the direction of Charmonia and Jets in proton-proton collisions as they get simulated by PYTHIA 8.2 Monash 2013. This thesis will make a prediction for what distance-correlation to expect between Jets and Charmonia of different transverse momenta.

Relevant for the understanding of particle physics is not only the data collected at experiments like ALICE but also the ability to make predictions of that data based on current models using simulation and to compare those predictions to the data. When data on the predicted correlation is collected at the ALICE detector, a comparison of the experimental data with this simulation should show potential flaws in the models used in PYTHIA to describe Charmonia production.

2 ALICE and LHC

The LHC is the largest particle accelerator in the world. It is a 27 km long synchrotron. Two beams of protons or heavy ions are accelerated into opposite directions, before they collide at one of the four particle detectors ATLAS, CMS, ALICE and LHCb. Each proton beam can be accelerated to energies of up to 6.5 TeV leading to a centre of mass energy of the collisions of up to 13 TeV. The LHC first started up in September 2008. [CERd]

The LHC is the final link in a chain of different accelerators to reach those high energies shown in figure 2.1. "Protons are obtained by removing electrons from hydrogen atoms. They are injected from the linear accelerator (LINAC2) into the PS Booster, then the Proton Synchrotron (PS), followed by the Super Proton Synchrotron (SPS), before finally reaching the Large Hadron Collider (LHC). Protons will circulate in the LHC for 20 minutes before reaching the maximum speed and energy.

Lead ions for the LHC start from a source of vaporised lead and enter LINAC3 before being collected and accelerated in the Low Energy Ion Ring (LEIR). They then follow the same route to maximum acceleration as the protons." [CER08]

In April 2018 the civil-engineering work on the High-Luminosity LHC (HL-LHC) begun. The HL-LHC aims to increase the Luminosity of the accelerator by a factor of ten, allowing it to collect more data at any given time. It should be operational from the end of 2027. [CERc]

ALICE (A Large Ion Collider Experiment) is one of the four particle detectors at the LHC. Its focus lies on the study of heavy-ion physics, specifically the collisions led ions. The ALICE collaboration studies the so called quark-gluon plasma, which can be produced in collisions of strongly interacting matter with very high energy densities. This quark-gluon plasma is similar to the conditions in the cosmos shortly after the big bang. The Detector is 26 m long, 16 m wide and 16 m high and weighs about 10.000 t. [CERa]



Figure 2.1: Schematic picture showing the CERN Accelerator Complex. [CER08]



Figure 2.2: Schematic picture showing the ALICE Detector with the different individual parts of the detector and the naming conventions for its coordinate system.[BC03]

The ALICE collaboration defines a coordinate system relative to the detector for consistent application in different works in [BC03]. The system can also be seen overlaid with a schematic picture of the detector in figure 2.2. In this coordinate system the transverse momentum is the sum of the momenta in x- and y-direction. The azimuthal angle ϕ is defined from 0 to 2π . In this work the angle in written as φ rather than ϕ .

One measurement that is not indicated in the coordinate system is the pseudorapidity η . The pseudorapidity is defined as $\eta := -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$, where θ is the angle between the beamline (*z*-axis) and the direction of the particle or Jet and thereby is a Lorentz invariant measure for the forward direction. $\eta = 0$ is pointing along the *y*-axis while $\eta > 0$ is indicating a direction partially in positive *z*-direction and $\eta < 0$ in negative *z*-direction. ALICE has an η -acceptance range of $-0.9 < \eta < 0.9$, which will be used in this work.

3 Theoretical Background

3.1 The Standard Model and the Strong Nuclear Force

The model currently in use to describe the world on the subnuclear level is the Standard Model of Particle Phyiscs (SM). According to current understanding matter and the interactions between matter consist of three types of elementary particles. Leptons and Quarks which are Fermions and messenger particles which are Bosons. The Leptons are the negatively charged electron, muon and tauon and the corresponding neutrinos. The six different quarks up, down, strange, charm, top and bottom are called flavours. The up, charm and top quark have an electric charge of +2/3, the down, strange and bottom quark have a charge of -1/3. Furthermore every quark has one colour charge, red, blue or green. The Leptons and Quarks are divided into three families or generations with increasing mass (see fig. 3.1). Every quark and lepton in the SM has a corresponding anti particle with the same mass, but opposite electric and colour charge. Anti particles are denoted with a bar over the symbol of the particle. For example an anti-down quark would be written as d.



Standard Model of Elementary Particles and Gravity

Figure 3.1: The particles of the Standard Model plus the theorised graviton. [Cus17]

In the SM there are three fundamental forces, each of which is communicated by a different boson: The electromagnetic force, which is communicated by photons, the weak nuclear force, which is communicated by W^{\pm} - and Z^{0} -bosons, the strong nuclear force, which is communicated by gluons. The force of Gravity is not included in the standard model, but is thought to be communicated by gravitons. However they have not been observed yet. The higgs boson is the particle responsible for the mass of the particles.

Most important for this work is the strong nuclear force, which couples to the colour charge of particles, binding quarks into bound states, as there cannot be free coloured particles.

The potential energy between two quarks consists of a -1/r Coulomb term from the electrostatic force and a term linear in r from the strong force, r being the distance between the two quarks (see fig. 3.2).

$$E_{\rm pot} = -\frac{A}{r} + Br \tag{3.1}$$

This means that two quarks cannot be separated, as the energy necessary for that would be infinite, a phenomenon known as Confinement. When enough energy is put into the separation of two quarks, for example in a high energy hadron hadron collision, the energy will be used to create new quark anti-quark pairs, forming new mesons (see fig. 3.2 b)). [Dem17]



Figure 3.2: a) Energy of the strong interaction between two quarks dependend on their distance (see eq. 3.1). b) Graphic representation of Confinement. The images are taken from [Dem17], but the captions are translated from German.

3.2 Charmonium

The most common form of Charmonium is called J/Ψ and was the first system observed containing the charm quark. Since its discovery in November 1974 the study of Charmonium has directly influenced the development of many methods in QCD. The same goes for the heavier Bottomonium which consists of a bottom and an anti-bottom quark.[Vol08]

There are different states of the Charmonium system. Figure 3.3 gives an overview of those different states. It can be seen that the ground state of the $c\bar{c}$ -system is the η_c not the J/Ψ particle, however J/Ψ is the most common state as η_c is very rare in pp collisions due to its spin correlation. J/Ψ has a rest mass of (3096.900 ± 0.006) MeV. Its first excited state is $\Psi(2S)$ with a rest mass of (686.097 ± 0.025) MeV.



Figure 3.3: "The level scheme of the $c\bar{c}$ states showing experimentally established states with solid lines. [...] In parentheses it is sufficient to give the radial quantum number and the orbital angular momentum to specify the states with all their quantum numbers. Only observed hadronic transitions are shown; the single photon transitions [...] are omitted for clarity." [Tan+18]

Charmonium and other "[h]adrons containing heavy quarks, charm or bottom, are excellent messengers of the quark–gluon plasma formed in [heavy ion] collisions. They are produced in the initial stages of the collisions, before the emergence of the plasma, and thus interact with the plasma constituents throughout its entire evolution, from its rapid expansion to its cooling and its eventual transformation into hadrons." [CERb] The quark-gluon plasma is of interested, because it is predicted to have been the state of matter in the very early stages of the universe ($\tau \approx 1 \,\mu$ s). However at collider experiments it can only be produced for very short periods of time in a very small volume, which is why it cannot be observed directly, making messengers like Charmonium even more important.[Feu17]

3.3 Jets and the anti- k_t algorithm

A Jet is a collimated spray of energetic hadrons that appear due to quarks or gluons fragmenting and hadronizing shortly after being produced. Jets can usually be identified by looking at an event display, but for the purpose of analysing events and to reconstruct the energy and direction of a Jet, a definition of a Jet is needed.

The Jet definition used in this work is the inclusive anti- k_t algorithm. This algorithm produces Jets that grow outward from particles with a high transverse momentum (hard "seeds") in a circular pattern. When two hard particles are close enough to each other, that their circular Jets would overlap without them being clustered into the same Jet, the harder particle forms the centre of a circular Jet, while the softer of the two forms a partially circular Jet, missing the area, where the two would overlap. The algorithm ensures the usage of hard seeds, by using the minimum of the inverse square of the transverse momentum in the distance measure (see eq. 3.2). Referring to this minimum also leads to the softer particles between two hard ones being clustered with the harder which produces the circular Jet around it and the Jet with the missing area around the softer of the two as described above.

One important measure to determine the quality of a Jet algorithm is its Infrared and Collinear (IRC) Safety. IRC Safety means, that the set of hard Jets that an algorithm finds should not be changed, when the analysed event is modified, by adding soft emissions or by a collinear splitting.[Sal10]

The anti- k_t algorithm is IRC safe.

This algorithm uses the following distance measures.

$$d_{ij} = \min\left(p_{Ti}^{-2}, p_{Tj}^{-2}\right) \frac{\Delta R_{ij}^2}{R^2}, \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2,$$

$$d_{iB} = p_{Ti}^{-2}$$
(3.2)

 d_{ij} is the distance between two particles *i* and *j* and d_{iB} is the distance between a particle *i* and the beamline. *y* is the pseudorapidity, φ the azimuthal angle and p_T the transverse momentum of the individual particles. *R* is a parameter of the algorithm called the Jet radius, as it determines the radius of the circular areas of the Jets.

Notably there is a generalised version of this distance measure, introducing the parameter p (see fig. 3.3). Note that [CS08] calls the transverse momentum k_T rather than p_T to differentiate it from the parameter.

$$d_{ij} = \min\left(p_{T_i}^{2p}, p_{T_j}^{2p}\right) \frac{\Delta R_{ij}^2}{R^2}, \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2,$$

$$d_{iB} = p_{T_i}^{2p}$$
(3.3)

Originally this was developed as the k_t algorithm, which used p = 1 and where anti- k_t with p = -1 gets its name. Another version of this is the Cambridge/Aachen (C/A) algorithm, which uses p = 0. This class of algorithms is called sequential recombination (SR_{p=x}) algorithms with the subscript in the abbreviation giving the value of the parameter p. Anti- k_t for example would be SR_{p=-1}.

Using a negative p has the advantage that it "favours clusterings that involve hard particles rather than clusterings that involve soft particles (k_t algorithm) or energy-independent clusterings (C/A)"[Sal10]. However the k_t and C/A algorithms produce substructures that can be usefully related to the QCD branching taking place in the event, whereas the anti- k_t does not. "[E]ssentially the anti- k_t recombination sequence will gradually expand through a soft subjet, rather than first constructing the soft subjet and then recombining it with the hard subjet".[Sal10]

With this distance measure established the algorithm then proceeds according to the following five steps.

- 1. Work out all the d_{ij} and d_{iB} according to equations 3.2.
- 2. Find the minimum of the d_{ij} and d_{iB}
- 3. If it is a d_{ij} , combine the particles i and j into a new particle and return to step 1.
- 4. Otherwise, if it is a d_{iB} , declare *i* a (final-state) jet, and remove it from the list of particles. Return to step 1.
- 5. Stop when no particles remain.

For a visual example, how the anti- k_t algorithm clusters an event with some hard and several soft particles and also a comparison to the three other IRC safe algorithms mentioned before, see fig. 3.4. Here it can also be seen how the algorithm generates circular Jets around hard seeds as described above, where the k_t and the Cambridge/Aachen algorithm do not produce circular Jets and the SISCone algorithm produces Jets that are less strictly circular and splits the overlapping area of two Jets rather than assigning it to the harder seed.



Figure 3.4: A sample event containing some hard particles together with some very soft, so called "ghosts", clustered with four different Jet algorithms, including anti- k_t , illustrating the active catchment area of the resulting hard Jets. For die k_t and the Cambridge/Aachen (in the figure abbreviated as Cam/Aachen) the specific shape depends of the "ghosts" and changes when they are modified.[CS08] Note that y is not the y coordinate in a euclidean coordinate system but the rapidity, so a measure for the polar angle.

For more details on the anti- k_t algorithm and Jet algorithms in general see [CS08] and [Sal10].

3.4 Direction of the Particles and Jets

Three properties of the Charmonia and Jets are considered for this thesis: Their transverse momentum p_T , their pseudorapidity η and their azimuthal angular direction φ as defined at the end of section 2. However the calculations of adding the momenta in x- and y-direction to get p_T or calculating η will not need to be done manually as both PYTHIA's Particle and FASTJET's Pseudojet Class (see section 4.1 and 4.3) safe not only p_x . p_y and θ but also p_T and η . Similarly one could calculate φ from p_x and p_y but it is also saved in the Classes.

4 Software

For this work several different open source software products were used.

4.1 Pythia

PYTHIA is a program to simulate high energy collisions. In its current state it works with pp, $\bar{p}p$, e^+e^- and $\mu^+\mu^-$ incoming beams. Previous versions of PYTHIA where implemented in Fortran 77 while the current version 8.2 is the second main release since a rewrite in C++.

The program was developed at the Swedish Lund University. The development of another program called JETSET, which was later merged with PYTHIA began in 1978.

[Sjö+14] describes how the relation between the complex final states of high energy collisions and the underlying physics is quite complicated for two reasons. "Firstly, we do not even in principle have a complete understanding of the physics. Secondly, any analytical approach is made intractable by the large multiplicities." To solve that Problem, PYTHIA generates complete events with Monte Carlo methods. "The complexity is mastered by a subdivision of the full problem into a set of simpler separate tasks. All main aspects of the events are simulated, such as hard-process selection, initial- and final-state radiation, beam remnants, fragmentation, decays, and so on. Therefore events should be directly comparable with experimentally observable ones."

PYTHIA has the following hard processes available internally.

- QCD processes which include both standard 2 → 2 with open charm and bottom production and 2 → 3.
- Electroweak processes include prompt photon production, single production of γ^*/Z and W^{\pm} , pair production of weak bosons with full fermion correlation for $VV \rightarrow 4f$ and photon collision processes of the form $\gamma\gamma \rightarrow f\bar{f}$.
- Onia include production of any ${}^{3}S_{1}$, ${}^{3}PJ$ and ${}^{3}DJ$ states of charmonium or bottomonium via colour-singlet and colour-octet mechanisms.
- **Top** production, singly or in pairs

- Fourth Generation fermion production via strong or electroweak interactions.
- Higgs processes include the production of the SM Higgs boson as well as the multiple Higgs bosons of a generic two-Higgs-doublet model (2HDM), with the possibility of CP violating decays. It is also possible to modify the angular correlation of the Higgs decay h → VV → 4f due to anomalous hVV couplings. The internal implementation of SUSY also uses the 2HDM implementation for its Higgs sector.
- **SUSY processes** include the pair production of SUSY particles as well as resonant production of squarks via the *R*-parity violating UDD interaction. Both squarks and gluinos can be made to form long-lived *R*-hadrons, that subsequently decay.
- New gauge boson processes include production of a Z', a W'[±] and of a horizontallycoupling gauge boson R⁰.
- Left-right symmetric processes include the production of the $SU(2)_R$ bosons W_R^{\pm} , Z_R^0 , and the doubly charged Higgs bosons H_L^{++} and H_R^{++} .
- Leptoquark processes singly or in pairs, with the assumption that the leptoquark always decays before fragmentation.
- **Compositeness processes** include the production of excited fermions and the presence of contact interactions in QCD or electroweak processes. The production of excited fermions can be via both gauge and contact interactions; however, only decays via gauge interactions are supported with angular correlation.
- Hidden Valley processes can be used to study visible consequences of radiation in a hidden sector.
- Extra-dimension processes include the production of particles predicted by Randall-Sundrum models, TeV-sized and Large Extra Dimensions, and Unparticles.

Most of these processes are not in any detail relevant for this work and are just mentioned here to give an overview over the physics of PYTHIA.[Sjö+14]

For a more in-depth description of the physics implemented also in PYTHIA 8.2 and a full bibliography see the PYTHIA 6.4 Physics and Manual [SMS06]. A list of all the authors, former authors and further contributors that are credited with the writing of PYTHIA can be found on the PYTHIA website [Sjö+].

In this work PYTHIA is used to simulate pp collisions at centre of mass energies of 13 TeV, which is the highest centre of mass energy achieved at the LHC.

4.2 FastJet

The Abstract of the User Manual for FASTJET Version 3.0.1 describes the software as "a C++ package that provides a broad range of jet finding and analysis tools. It includes efficient native implementations of all widely used $2 \rightarrow 1$ sequential recombination jet algorithms for ppand e^+e^- collisions, as well as access to 3rd party jet algorithms through a plugin mechanism, including all currently used cone algorithms. FASTJET also provides means to facilitate the manipulation of jet substructure, including some common boosted heavy-object taggers, as well as tools for estimation of pileup and underlying-event noise levels, determination of jet areas and subtraction or suppression of noise in jets."[CSS11]

In this work FASTJET is going to be used to run the anti- k_t Jet algorithm with a radius of R = 0.4. The algorithm represents the Jets as Objects of the Class Pseudojet, which will then be used analogous to the Particle Class from PYTHIA to read out properties like the transverse momentum or the direction of the Jets.

4.3 ROOT

ROOT is an open source data analysis framework. The development project is coordinated by CERN. ROOT provides a programming interface and a graphical user interface, it is written in and relies on C++.[PQZ]

In this work the framework is mainly used to create, manipulate and analyse histograms, including weighing and normalising the input and calculating the standard deviation to measure the widths of the distributions.

5 Simulation and Analysis

5.1 Goal

The following simulation will look into the correlation between the production of Jets and Charmonia as predicted by PYTHIA. The analysis will focus on how this correlation changes with the transverse momentum of both the Jets and Charmonia. The goal is to provide a prediction, which can later be compared to experimental data collected at the ALICE detector. This comparison should show potential shortcomings in PYTHIA's models for Charmonium production and might help to improve on those for new tunes of the program.

5.2 Distance Measure

To compare the directions of Charmonia and Jets a measurement for their relative distance from another needs to be defined. For that purpose the analysis compares the azimuthal angle φ and the pseudorapidity η (see section 3.4).

Since η is Lorentz invariant, the difference between two values is a sufficient measure for the distance in that direction (see eq. 5.1). This produces negative values for $\Delta \eta$ which serve as a check for symmetry and will make it easier, to get the standard deviation the distribution, as the entire peak including the negative part will be plotted and not only the positive half of the peak, so that an interval symmetrical around the expected mean can be used to get the deviation. Physically a distance should naturally only be positive. To arrive at that result the absolute values of the differences would have to be considered. However to gain the computational advantage in regards to the standard deviation and the check for symmetry, this work will allow negative values.

$$\Delta \eta = \eta_{\text{Jet}} - \eta_{\text{Charmonium}} \tag{5.1}$$

The φ -angle is not as straightforward. The fact that is circles around from 2π to 0 means, that simply forming the difference of a particle just under 2π and one just over 0 would show them as having a distance of just under 2π and not nearly 0 as it should be. So to avoid that,

 2π is added to the difference if it is smaller than $-\frac{\pi}{2}$ and subtracted from it if it is larger than $\frac{3\pi}{2}$ (see eq. 5.2). Again the distance should naturally go from 0 to π while in this case it goes from $-\frac{\pi}{2}$ to $\frac{3\pi}{2}$. But that leads to the angles of 0 and π each being in the middle of an interval, so that the standard deviation can be read out.

$$\Delta \varphi = \varphi_{\text{Jet}} - \varphi_{\text{Charmonium}} \begin{cases} +2\pi \quad \varphi_{\text{Jet}} - \varphi_{\text{Charmonium}} < -\frac{\pi}{2} \\ +0 \quad -\frac{\pi}{2} \le \varphi_{\text{Jet}} - \varphi_{\text{Charmonium}} \le \frac{3\pi}{2} \\ -2\pi \quad \varphi_{\text{Jet}} - \varphi_{\text{Charmonium}} \ge \frac{3\pi}{2} \end{cases}$$
(5.2)

Also it is important to note, that PYTHIA's and FASTJET'S .phi() function use different measures for φ . PYTHIA defines it to go from $-\pi$ to π and FASTJET uses a definition from 0 to 2π , like the ALICE coordinate system [BC03]. However FastJet also has a function .phi_std() which uses the definition from $-\pi$ to π , which will be used for this work as to avoid complications with the definitions. This does not lead to problems with the definition of the ALICE coordinate system, as the difference between two angles does not depend on a linear offset, so to be consistent, it is only important to use the same definition for both values.

5.3 Simulation

The collision system is pp-collision at a centre of mass energy of 13 TeV. PYTHIA allows to simulate events in different momentum transfer (\hat{p}_T) ranges. A higher \hat{p}_T increases the amount of produced Charmonia, especially those with higher transverse momenta. Setting a higher \hat{p}_T therefore allows for more statistics with less events simulated. The used ranges are 7 to 20, 20 to 50, 50 to 80 and 80 to 100 GeV. For the final analysis 100 Million events per \hat{p}_T range get simulated. For the simulation all hard QCD process are turned on, which is also the reason, \hat{p}_T starts at 7 GeV rather than 0: The pertubative cross section tends towards infinity for small \hat{p}_T . The Tune used is Monash 2013, the standard tune for PYTHIA 8.2. For the Jet parameter R (eq. 3.2) a value of 0.4 is chosen.

For every simulated event the transverse momentum p_T , azimuthal angle φ and pseudorapidity η of every Charmonium and every Jet are saved for the analysis. The Charmonia are identified using the Monte Carlo particle numbering scheme.

Different states of the Charmonium-system are not differentiated, but a check for the daughter particles ensures, that Charmonia decaying into other Charmonia are not double counted. In other words, every particle, that is a meson, containing a charm and an anti-charm quark and does not decay into another meson containing a charm and an anti-charm quark gets recorded.

5.4 Analysis

For the purpose of this analysis the Jets and Charmonia are sorted into p_T intervals. The intervals for the Jets start at 5 GeV and are separated at 20 GeV, 40 GeV and so on until the last interval includes all Jets with a p_T of at least 80 GeV. The Charmonia intervals start at 0 and go up in steps of 5 GeV with the last interval containing all Charmonia with a p_T greater than 20 GeV. These intervals were chosen by considering the p_T spectrum of both Charmonia and Jets (see fig. 5.1). While it is interesting to look at all Charmonia that were generated in the collision, it is helpful to filter out Jets that are too soft, as they do not actually give insight into the structure of the event, but are just the result of the algorithm clustering all particles into Jets, even when those Jets are not physically meaningful. Therefore the lowest Charmonium interval starts at 0, while the lowest Jet interval starts at 5 GeV.



Figure 5.1: p_T -spectrum of the Charmonia and Jets.

For all combinations of the intervals of Jets and mesons the distance of each meson from each Jet is calculated, resulting in the heatmaps in figure 5.3. However to first get an idea of the distribution, the distance of all Jets and Charmonia is considered (see 5.2). This still only includes Jets with a p_T of at least 5 GeV but apart from that no further differentiation is made.



Figure 5.2: η - and φ distance of all Jets from all Charmonia. The colouring scheme for the z-axis is normalised in arbitrary units proportional to the differential cross section.

It is visible that there is a cluster around $\Delta \varphi = 0$, $\Delta \eta = 0$. There appears to be a ring of missing data which intersects the axes at about ± 0.4 . This is due to the Jet-radius R from the Jet definition (see eq. 3.2) which was chosen to have a value of 0.4. However this ring is still filled up with enough statistic. Therefore is it easier to see in in the comparison of low p_T Jets with high p_T Charmonia in 5.3. The complete heatmap in 5.2 and the comparison of low p_T Jets with low p_T Charmonia in 5.3 have enough statistics to fill up the ring, while the comparisons with higher p_T Jets have so little statistic, that the ring is not visible yet.

Also there is a cluster at $\Delta \varphi = \pi$ that shows not correlation in $\Delta \eta$. This is expected due to many events with a Jet having a second Jet in the opposite φ -direction to conserve the transverse momentum. But there is no correlation between the η -direction of these two Jets, which is why the Charmonia in the Jets in one direction ($\Delta \eta = 0, \Delta \varphi = 0$) show a correlation of $\Delta \varphi = \pi$ but no correlation in η .

However these heatmaps just visualise the changes with the momenta. To quantify the changes the standard deviation RMS (Root Mean Square) of the differential cross sections with $\Delta \varphi$ and $\Delta \eta$ is considered.



Figure 5.3: Heatmaps of the distances of the Charmonia from the Jets. The p_T of the Charmonia increases left to right, the p_T of the Jets bottom to top. The colouring scheme for the z-axis is normalised in arbitrary units proportional to the differential cross section the same way as the heatmap in figure 5.2.

Specifically the values for $\Delta \eta$ with $|\Delta \varphi| < 1$ are used as they are the values that are actually correlated. The exact cutoff point of 1 is somewhat arbitrary and only chosen in hindsight based on an evaluation of the heatmaps.

To make sure to only consider the mean and deviation of the actual peak, especially in $\Delta\varphi$ direction, where two separate peaks are to be considered, the ranges of the axes are limited to the areas of the peaks. The two peaks in $\Delta\varphi$ direction are called the near- and farside peak respectively. Those ranges are going to be symmetrical around the expected mean (0 for the $\Delta\eta$ peak and the $\Delta\varphi$ nearside peak and π for the $\Delta\varphi$ farside peak) with a range of \pm 0.6. Similar to the $|\Delta\varphi|$ cutoff point for which $\Delta\eta$ values to consider, the value of 0.6 is chosen in hindsight by estimating the peak widths.

Again first the peaks for the comparison of all Jets to all Charmonia (see fig. 5.4) are considered to convey an idea of the general shape of the distribution.



Figure 5.4: Peaks for the comparison of all Jets and Charmonia. The $\Delta \eta$ peak has an RMS of 0.202, the $\Delta \varphi$ nearside peak of 0.151 and the farside peak has an RMS of 0.363.

As is already visible in fig. 5.3 there is very little statistics for the high Jet p_T , especially for the combination with low Charmonia p_T . Accordingly the shapes of the distributions of these intervals are much less clear and the uncertainties of the values are much higher. As examples the plots for the lowest and highest p_T intervals are shown in fig. 5.5 and 5.6. So the comparison of Charmonia with 0 to 5 GeV and with more than 20 GeV to Jets with 5 to 20 GeV and with more than 80 GeV. All 50 graphs are shown in grids similar to fig. 5.3 in the Appendix (fig. A.1 and A.2).

Relevant to quantify the strength of the correlation between Charmonia and Jets is the width of those peaks. As mentioned before this is indicated by the RMS; the smaller the RMS is the stronger is the direction-correlation. Specifically interesting is how it changes with the different transverse momenta of Jets and Charmonia. So for each interval of the Jet p_T the RMS change with the p_T of the Charmonia is considered and vice versa. This comparison of



Figure 5.5: The Peaks in $\Delta \eta$ -direction. Left Charmonia with p_T from 0 to 5 GeV, right Charmonia with more than 20 GeV, top Jets with p_T over 80 GeV and bottom Jets with p_T from 5 to 20 GeV. Especially for the comparison of high p_T Jets to low p_T Charmonia (a) there is not enough statistics to even see a peak. However it is clearly visible that the peaks with high p_T Charmonia are much sharper than the visible one with low p_T Charmonia.

five intervals each and three different peaks, which RMS values are compared leads to thirty graphs. Figure 5.7 shows a few examples of those thirty graphs, all of them can be found in the appendix in section A.2.

In most cases a downward trend can be observed like in the three plots in fig. 5.7. The least strongly this can be seen for the farside peak in $\Delta \varphi$ -direction (fig. A.7 and A.8). This is to be expected since the farside peak is the smallest of the three peaks, therefore the lack of statistics leads to the greatest fluctuations with some of the developments showing upwards trend or no discernible pattern at all. However as in the example in fig. 5.7 generally a downward trend with some outliers can be seen here as well.

Another break with the pattern is the development with the p_T of the Jets when comparing them to Charmonia with a low p_T (0 to 5 GeV) (fig. 5.8). The farside peak shows a slight downward trend with an outlying datapoint for the Jet p_T interval from 20 to 40 GeV, however in both the $\Delta \eta$ and the nearside peak an upward trend can be observed, so the correlation



Figure 5.6: The Peaks in $\Delta \varphi$ -direction. Left Charmonia with p_T from 0 to 5 GeV, right Charmonia with more than 20 GeV, top Jets with p_T over 80 GeV and bottom Jets with p_T from 5 to 20 GeV. Especially for the comparison of high p_T Jets to low p_T Charmonia (a) there is not enough statistics to even see a the nearside peak, while at the position of the farside peak there is a single high datapoint with an uncertainty high enough that it might still belong to the background. However it is clearly visible that the nearside peaks with high p_T Charmonia are much sharper than the visible one with low p_T Charmonia. The farside peaks are visible but not high enough to make a comparison just by looking at the plots.

between low p_T Charmonia seems to decrease with the p_T of the Jets. However as discussed before these are exactly the intervals in which the least data was collected in the first place. So the apparent decrease in correlation might not be due to any physical processes but mainly due to a lack of statistics.

Finally it can be observed that the downward trend tends to get steeper in the higher p_T ranges. An example of this can be seen in figure 5.9. When looking at the development of the RMS of the $\Delta \eta$ Peak with the p_T of the Charmonia it starts out at a higher value for the low p_T Charmonia, when those are compared to higher p_T Jets, but the following decrease is also much steeper, arriving at a similar minimal value for the RMS already for lower Charmonia p_T . However it needs to be said, that the higher initial value is due to the increase of the RMS with the Jet p_T when compared to low p_T Charmonia discussed before and the difference in



Figure 5.7: Example for the changes of the width of the RMS with the p_T of the Charmonia compared to Jets with p_T between 5 and 20 GeV. The datapoints are marked at the lowest point of the Charmonium p_T interval. So the point for the interval from 0 to 5 GeV is marked at 0 GeV, the one for the interval from 5 to 10 GeV at 5 GeV etc. (a) is the peak in $\Delta \eta$ -direction, (b) the nearside peak in $\Delta \varphi$ -direction and (c) the farside peak in $\Delta \varphi$ -direction with $\mu = \pi$. The changes with the p_T of Charmonia compared to Jets with other p_T and the changes with the p_T of Jets can be found in the appendix in section A.2.

the downward trend for Charmonia with a higher p_T is very slight and might therefore be due to statistical fluctuations and cannot be considered a conclusive result.



Figure 5.8: Development of the RMS with the p_T of the Jets when they are compared to low p_T (0 to 5 GeV) Charmonia.



Figure 5.9: Development of the RMS of the $\Delta \eta$ peak with the p_T of the Charmonia when they are compared to Jets with a p_T of 20 to 40 GeV and a p_T of 60 to 80 GeV

6 Conclusion and Outlook

The direction-correlation of Jets and Charmonia seems mostly to increase with the transverse momenta of both the Jets and the mesons. This increase can be observed for the η correlation and for both peaks in the φ correlation. The main outlier is the correlation of Jets with low p_T Charmonia which seems to decrease with increasing Jet p_T . However in the events with those high momentum Jets, the Charmonium production is very low leading to very little statistics for those comparisons. Therefore the observed decrease in distance-correlation seems more likely to be a result of a decrease in Charmonium production than an actual increase in the expected distance between the two.

Similarly the trend of an increase in distance-correlation with an increase in transverse momentum could not be seen as clearly in the farside $\Delta \varphi$ peak. However since this peak does not show a correlation in η it is expected that a lot of the farside Jets are not within the η -acceptance range of the ALICE detector and therefore cannot be seen, leading to much less statistics for the farside peak compared to the nearside one. Therefore the greater fluctuation in the correlation is most likely due to this lack of statistics.

So to get more conclusive results about both of these outliers and about the exact shape of the downward trend in RMS more statistics would need to be collected.

However this analysis can still be greatly expanded upon apart from the simulation of more data. For one it is possible to differentiate between different states of Charmonium and consider for example how specifically the correlation between J/Ψ or $\Psi(2S)$ and Jets changes. Especially the former might also lead to more conclusive results as during the writing of this work, Nicolas Tiltmann has found in his bachelor thesis [Til20] that PYTHIA's Monash 2013 tune is at least qualitatively in agreement with the experimental data for J/Ψ production, whereas the "prediction of $\Psi(2S)$ production is much more imprecise".

Similarly this work can be expanded upon by also considering Bottomonium. As mentioned in section 3.2 it is relevant to the study of the strong force for similar reasons to Charmonium.

Further analysis could include different p_T intervals for the Jets and Charmonia, a look at other tunes or how specific processes that can be individually turned off and on in PYTHIA effect the results. But as laid out in the introduction of this work and section 5.1 these predictions and the potential expansions of them are only the first step. When the HL-LHC is operational and ALICE is collecting data again, that data should also be analysed with regards to the correlation between Jets and Charmonia that has been looked at here as to allow for a comparison between the results of this simulation and the experimental data. The last step will then be to find the reasons for potential differences to improve the models implemented in PYTHIA.

A Appendix

A.1 $\Delta\eta$ - and $\Delta\varphi$ -Peaks



Figure A.1: The $\Delta \eta$ Peaks for all p_T intervals. The p_T of the Charmonia increases left to right, the p_T of the Jets increases bottom to top. The four plots in the corners are shown in fig. 5.5



Figure A.2: The $\Delta \varphi$ Peaks for all p_T intervals. The p_T of the Charmonia increases left to right, the p_T of the Jets increases bottom to top. The four plots in the corners are shown in fig. 5.6

A.2 RMS Changes

As in the example in fig. 5.7 the datapoints are marked at the lowest point of the Charmonium or jet p_T interval respectively. So for the changes with the Charmonium p_T the point for the interval from 0 to 5 GeV is marked at 0 GeV, the one for the interval from 5 to 10 GeV at 5 GeV etc. and analogous for the changes with the jets p_T the point for the interval from 5 to 20 GeV is marked at 5 GeV etc.



Figure A.3: The Changes of the RMS of the $\Delta \eta$ Peak with the p_T of the Charmonia. The p_T intervals of the jets are indicated below the individual figures.



Figure A.4: The Changes of the RMS of the $\Delta \eta$ Peak with the p_T of the jets. The p_T intervals of the Charmonia are indicated below the individual figures.



Figure A.5: The Changes of the RMS of the $\Delta \varphi$ nearside Peak with the p_T of the Charmonia. The p_T intervals of the jets are indicated below the individual figures.



Figure A.6: The Changes of the RMS of the $\Delta \varphi$ nearside Peak with the p_T of the jets. The p_T intervals of the Charmonia are indicated below the individual figures.



Figure A.7: The Changes of the RMS of the $\Delta \varphi$ farside Peak with the p_T of the Charmonia. The p_T intervals of the jets are indicated below the individual figures.



Figure A.8: The Changes of the RMS of the $\Delta \varphi$ farside Peak with the p_T of the jets. The p_T intervals of the Charmonia are indicated below the individual figures.

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