LU-TP 20-37
June 2020

Investigation of Impact Parameter Profiles in Multi-Parton Interactions

Martin Korsfeldt

Department of Astronomy and Theoretical Physics, Lund University

Bachelor thesis supervised by Leif Lönnblad

LUNDS UNIVERSITET

Abstract

The purpose of this thesis was to implement an alternative method to calculate the overlap function, which describe to what extent two protons overlap with each other spatially, into PYTHIA8 in order to determine how it affected the average number of multiparton interactions. The new overlap function is based on an explicit impact parameter picture, whereas PYTHIA8s overlap function uses an implicit impact parameter picture. This new overlap function was calculated using the Glauber formalism, as well as the Good-Walker formalism, both used by the Angantyr model, and by identifying appropriate terms in the overlap function that PYTHIA8 used. Using this new overlap function, simulations were run to compare the new overlap to default PYTHIA8 and default Angantyr. Despite the new overlap function being unintuitive, the results show that it is potentially viable once it has been tuned to data, and when decisions have been made regarding some parameterisations in the new overlap function.

Populärvetenskaplig beskrivning

När en utredare observerar en olycksplats är bevisen de kan hitta viktiga. Bevisen är det som gör att de kan återskapa hur olyckan hände och förstå vad som hände. Men om de inte förstår bevisen, eller använder dom för att återskapa olycksplatsen på fel sätt, kan svaret de får vara fel. Inom partikelfysik kolliderar vi atomkärnor med extrema energier för att se vilka hemligheter universum har. För att återskapa scenen för dessa olyckor använder vi så kallade händelsegeneratorer.

Det är där vi stöter på ett problem, eftersom det verkar som om vi inte återskapar dessa partikelbilkrascher på rätt sätt. Det vi för närvarande gör fel är att vi använder en felaktig modell av den så kallade impact-parametern. I en bilkrasch skulle impact-parametern likna hur bilarna kraschar in i varandra, vilket kan vara allt från en frontalkollision eller en kantstöt. Just nu simuleras kollisionerna som om impact-parametern inte har en direkt påverkan på hur mycket bilen förstörs, vilket innebär att en kantstöt skulle kunna förstöra en bil lika mycket som en frontalkollision vid samma hastighet. Detta är inte hur en bilkrasch händer, och det borde inte heller vara hur partiklar kolliderar. Partikeldetektiverna har bestämt sig för att lösa problemet genom att ändra händelsegeneratorn så att det spelar roll på vilket sätt atomerna kolliderar.

Alla dessa ändringar görs så att det kan hjälpa oss att undersöka det tidiga universum. Forskare tror att förutsättningarna för det tidiga universum kan återskapas genom att kollidera mycket tunga atomer, som bly, med varandra. Det slutgiltliga målet med Angantyrprojektet är att skapa ett kvark-gluon plasma, vilket det tidiga universum misstänks har varit gjort av, och berätta hur det fungerar.

Contents

1 Introduction

Event generators are used in high energy physics to simulate particle interaction events that occur at particle colliders, such as proton-proton collisions, using (pseudo) random number generators [1]. The reason such number generators are used is due to the inherently stochastic nature of quantum mechanical processes. In such collisions the particles have been accelerated to velocities close to the speed of light, and because of that are Lorentz contracted to the point that the interacting particles can be treated as discs rather than spheres. The results of such simulations can then be compared to data gathered at particle accelerators to determine how good the event generator is at describing the measured data. An event generator that is able to accurately reproduce measured data can then be used to make predictions about particle interactions. This thesis will be working with the most common of such event generators, PYTHIA8 [1].

This thesis will deal with the bulk of collisions, known as minimum bias events. The majority of these events have low momentum transfers, and there is a high chance for the protons to undergo a non-diffractive interaction which is when the protons completely break up [2]. In the current implementation of PYTHIA8 there are two ways of doing this, the native PYTHIA8 method [3], and the Angantyr method [2], which is used to simulate heavy-ion collisions. Even though Angantyr is built for heavy-ion collisions it can simulate proton-proton collisions, which is what will be studied in this thesis, as it is the simplest case of ion collisions. Minimum bias events are not often looked at with as much interest as the extremely high momentum transfer interactions, like the ones most often studied at CERN, where they are used to search for new particles, such as the Higgs Boson that was discovered in 2012.

Protons, like all hadrons, are not pointlike particles. They have a substructure and their constituent particles, quarks and gluons, are collectively called partons. When protons are scattered at particle accelerators there is enough energy to have the individual partons interact and give rise to new particles. In these interactions it is possible to have more than one pair of partons interacting in the same proton-proton collision, and this is known as multiparton interactions [3], sometimes shortened to MPIs. An example of this can be seen in Figure 1, where two protons are collided and their overlapping area represents the area where multiparton interactions can take place.

As can be seen from Figure 1, the overlap is extremely important in regards to multiparton interactions as the number of interactions is directly tied to the size of the overlap, which is simply a representation of how many partons are available to interact with each other. Given all of this, it might be a surprise that native PYTHIA8 does not use an explicit geometrical picture to describe the collision [3]. It uses an implicit geometrical image of this scenario to derive the overlap function, which in turn is used to randomly pick the average number of interaction in any given event. The reason it can only give an

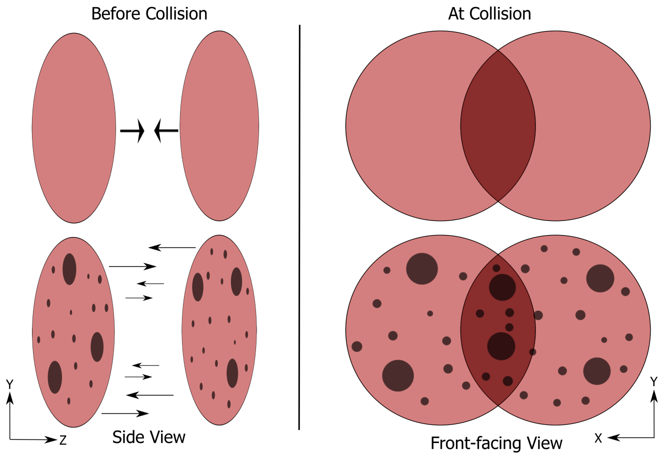


Figure 1: Schematic image of two protons colliding. Left side is a side view of the protons travelling towards each other. The protons are represented as ovals due to lorentz contractions. Right side is the view along the beam pipe of an accelerator at the time of collision. The top row shows the interaction between two protons without an internal structure. The bottom row shows interaction with substructure. The dark circles represent partons, with smaller circles being sea quarks and gluons, while larger circles represent the valence quarks of the proton.

average number is due once again to the inherently stochastic nature of these interactions, where it is impossible to predict the number of interactions for any individual event. Not only can we only get an average number of interactions, but that average number can vary greatly depending on the width of the assumed overlap function, from as few as a single interaction, to around thirty [4].

This differs from the Angantyr model, which relies on an explicit geometrical picture. This is because Angantyr is used to simulate heavy-ion collisions [2], and in such a scenario it must be explicit in order to determine which nucleon interacts with which. If it was not an explicit picture, an entire heavy-ion would be interpreted as simply one massive hadron, leading to a vast increase in the complexity of the calculations. This explicit picture is also potentially useful in trying to calculate the number of multiparton interactions that occur, using an overlap function that is dependent on the impact parameter, b, which represents the distance between the centers of the two colliding protons [2].

The intent of this thesis is to investigate the effects on the simulated results if one alters the code of PYTHIA8 such that it supports an alternative method to calculate the overlapping area of interacting particles based on the explicit impact parameter picture used by Angantyr [2]. The current overlap function that is used by PYTHIA8 is implicit with regards to the impact parameter, while Angantyr's method is explicit. PYTHIA8 already supports several different ways to calculate the overlap area [1], as there is not yet a consensus as to what method correctly describes the overlap function. The addition of Angantyr's method is to give a more consistent picture of heavy-ion collisions so that the way Angantyr chooses which nucleons interact also influences the number of multiparton interactions occur in the individual sub-collisions [5].

The next section consists of the theory required to understand this subject on a level beyond what this introduction can convey, specifically a deeper dive into the math and physics of MPIs, and how it is implemented in PYTHIA8 and how it is impacted by the changes that Angantyr makes. After this, in section 3, a new method of calculating the overlap function will be presented, which is then followed in section 4 by the results of the simulations that were run once this new overlap function was implemented, as well as interpretations of these results. Finally the issues with this new overlap function will be discussed in section 5, and the conclusions that can be drawn from the results will be presented in section 6.

2 Background Theory

The explanation above is obviously not sufficient to understand the changes and impacts that the addition of the Angantyr method has on PYTHIA8. To reach such an understanding the concept of multi-parton interactions needs to be more thoroughly explained with a grounding in mathematics and physics rather than a hand-waving explanation. The current state of the multi-parton interactions machinery of PYTHIA8 also needs to be explored to understand how the Angantyr method alters it.

Then, of course, the changes that Angantyr implements need to be described in far greater detail. The Angantyr model [2] is largely based on the Glauber model [6], which describe which nucleons interact with each other, and the Good-Walker formalism [5][7], which describe how those nucleons interact. Both of these make use of quantum mechanical calculations, and must therefore be described thoroughly.

2.1 MPIs, A Mathematical Description

Most of the following two sections are based largely on the PYTHIA6 manual [1]. As described before, multiparton interactions is when more than one pair of partons interact in colliding hadrons. The total rate of this type of interaction is assumed to be given by perturbative QCD [1][8]. Due to the way the strong force behaves, the cross sections for such processes increases rapidly at lower transverse momentum, $p_\perp$, leading to a divergence of the cross section as $p_\perp \to 0$. This requires a cut-off of the $p_\perp$, known as $p_{\perp_{min}}$. The interactions between these pairs of partons can be considered to take place independently, and can therefore have the number of interactions be given by a Poisson distribution [1].

The description above has described hadrons as composite, but not necessarily as extended, objects. If this fact is included, it lowers the rate, as the number of interactions should be lower in an edge-edge collision than in a head-on collision. The distribution is still Poissonian in a given collision, but the average number is lowered, and the precise way that it is lowered depends on what matter distribution is assumed [1]. It should be said that in the end, the overall distribution is non-Poissonian due to $n = 0$ corresponding to no event, as well as the effects of energy-momentum conservation and Parton Density Function (PDF) rescaling.

The cross section for a hard QCD $2 \to 2$ process, which is what we are interested in, is given by:

$$\frac{d\sigma}{dp_\perp^2} = \sum_{i,j,k} \int dx_1 \int dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}_{ij}^k}{dp_\perp^2}. \tag{1}$$

The x_1 and x_2 represents the fractions of momentum that the two interacting partons carry. The f_i and f_j represent the PDFs of the two interacting partons of flavours i and j, and Q^2 represents the energy scale of the scattering. The $\hat{\sigma}_{ij}^k$ derivative represents the individual parton-parton cross sections, iterated over all of the possible channels, k. This is summed over all possible flavours and channels to give a full hadron-hadron cross section.

The cross section for hard scatterings, σ_{hard} above some minimum transverse momentum, $p_{\perp min}$, is given by [1]

$$\sigma_{hard}(p_{\perp min}) = \int_{p_{\perp min}^2}^{s/4} \frac{d\sigma}{dp_\perp^2} dp_\perp^2, \tag{2}$$

where s is the center of mass energy. The upper limit of the integration is the square of half of the center of mass energy: $(\sqrt{s}/2)^2 = s/4$, which is the most energy a body can get in a two body collision. This hard cross section can be compared to the full non-diffractive cross section, $\sigma_{non-diff}$. This ratio can easily be larger than unity, which is not a contradiction, as the σ_{hard} does not give the cross section for the hadron, but for the individual partons. A number larger than unity simply implies that there was more than one parton-parton interaction in that particular hadron-hadron interaction. This leads to the average number of parton-parton interactions above a certain threshold $p_{\perp min}$ being simply [1]

$$\langle n \rangle = \frac{\sigma_{hard}(p_{\perp min})}{\sigma_{non-diff}}. \tag{3}$$

Note that this is in the Poissonian case.

2.2 PYTHIA8s Current Implementation

The current way that multiparton interactions are implemented in PYTHIA8 relies on a spherically symmetric matter distribution inside of the hadron, or in mathematical terms:

$\rho(x)d^3x = \rho(r)r^2 \sin\theta dr d\theta d\phi$ [1]. The radial matter distribution can have several different shapes, ranging from a single Gaussian, a double Gaussian, to an exponentially decreasing function. Regardless of the specific shape, if two such matter distributions collide with an impact parameter b, the time integrated overlap function becomes [1]:

$$\mathcal{O}(b) \propto \int dt \int d^3x \rho(x,y,z)\rho(x+b,y,z+t). \tag{4}$$

As stated in the introduction, the larger the overlap area, the more likely it is for partons to interact. In PYTHIA8, the relationship is linear, and is stated as [1]:

$$\langle \tilde{n}(b) \rangle = k\mathcal{O}(b), \tag{5}$$

where $\tilde{n}$ is the number of parton-parton interactions when two hadrons collide with and impact parameter b, and k is related to the parton-parton cross section. Note that the average number of interactions is dependent on the impact parameter.

PYTHIA8 requires that in each event there is at least one interaction above a certain cutoff value, $p_{\perp min}$ [1]. It is important to note here that normally the cutoff is simply a value, below which no interactions are allowed. However, PYTHIA8 has replaced this "hard" cutoff with a "soft" suppression, which is given by [1]

$$p_{\perp 0}(s) = (2.28 \text{ GeV})\left(\frac{\sqrt{s}}{7 \text{ TeV}}\right)^{0.215}, \tag{6}$$

The $2 \to 2$ cross section is dominated by t-channel gluon exchange, therefore it diverges as $\frac{1}{p_\perp^4}$ as $p_\perp \to 0$. This was fixed in the previous section by the hard cut-off $p_{\perp min}$, so:

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s(p_\perp^2)}{p_\perp^4}\Theta(p_\perp - p_{\perp min})$$

This is now fixed by the more realistic, soft cut-off:

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s(p_\perp^2)}{p_\perp^4} \to \frac{d\sigma}{dp_\perp^2} = \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}. \tag{7}$$

In eq. (6) s is the center of mass energy. The physical interpretation of eq. (7) is that at low $p_\perp$ the gluon density becomes very high. At such high densities it is difficult to differentiate between the gluons, leading to the gluons "shadowing" each other, leading to a sort of saturation. It is this divergence in the gluon density that is better modelled by a gradual suppression rather than a unphysical hard cutoff. However, once this is taken into consideration, the simplified picture that was shown in figure 1 is no longer correct, as the gluons (which would make up a large fraction of the partons in figure 1) would now overlap with each other, which is the "shadowing" that was described previously. If the matter distribution has a tail that approaches zero for large impact parameter, which is the case for the ones listed above, there is a possibility to have an event where there is no interactions. For the purposes of this thesis, we are interested in non-diffractive collisions where there is at least one parton-parton interaction. The probability, according to Poisson statistics, for two protons to collide with at least one non-diffractive interaction is then given by [1]:

$$\mathcal{P}_{int}(b) = 1 - \exp(-\langle \tilde{n}(b) \rangle) = 1 - \exp(-k\mathcal{O}(b)). \tag{8}$$

This leads to the average number of interactions per event to become [1]:

$$\langle n(b) \rangle = \frac{\langle \tilde{n}(b) \rangle}{\mathcal{P}_{int}(b)} = \frac{k\mathcal{O}(b)}{1 - \exp(-k\mathcal{O}(b))}. \tag{9}$$

The relation $\langle n \rangle = \frac{\sigma_{hard}}{\sigma_{non-diff}}$ must still hold true, and therefore, the numerator and denominator must be integrated over b, separately, becoming [1]:

$$\langle n \rangle = \frac{\int \langle n(b) \rangle \mathcal{P}_{int}(b) d^2b}{\int \mathcal{P}_{int}(b) d^2b} = \frac{\int k\mathcal{O}(b) d^2b}{\int 1 - \exp(-k\mathcal{O}(b)) d^2b} = \frac{\sigma_{hard}}{\sigma_{non-diff}}. \tag{10}$$

Obviously the average number of interactions no longer explicitly depends on the impact parameter. If this equation is studied, one can see that fluctuation of the impact parameter (or any variable that induces non-Poissonian fluctuations in the number of MPIs on an event-by-event basis) can lead to a large change in the average number of parton-parton interactions.

2.3 The Glauber and Good-Walker Formalisms

Most of the following section is based on the Angantyr paper by Bierlich et al [2]. Angantyr makes use of the so-called Glauber formalism [6], which is formulated in impact parameter space. This allows for cross sections to be interpreted directly as probabilities. This will be of great use when trying to interpret the Good-Walker formalism [2]. Glaubers original paper [6] did not include fluctuations in the nucleon-nucleon cross section. Without these fluctuations the model treats the hadrons as completely opaque, solid disks, so if the impact parameter is smaller than the added radii of the interacting hadrons, then the hadrons will interact. The Angantyr version [2] of the Glauber model does include fluctuations, which relates the fluctuations to the diffractive cross section in accordance with the so-called od-Walker formalism, which Angantyr also makes use of.

For particles with a substructure, it is possible that the mass eigenstates are not the same as the elastic interaction eigenstates [5]. Denoting the mass eigenstates with Ψ_i, the projectile protons mass eigenstate with Ψ_0, and with Φ_l being the eigenstates of the scattering amplitude, such that $T\Phi_l = t_l\Phi_l$. The mass eigenstates is a linear combination of scattering eigenstates [5]:

$$\Psi_i = \sum_l a_{il}\Phi_l.$$

This leads to the elastic amplitude of the ground state projectile being given by [5]:

$$\langle \Psi_0|T|\Psi_0\rangle = \sum_l |a_{0l}|^2 t_l = \langle T\rangle \,.$$

With the elastic cross section given by [2]:

$$\frac{d\sigma_{el}}{d^2b} = \langle T(b)\rangle^2 \,.$$

Doing the same with diffractive scattering (which includes elastic scattering), using that it is the sum of the transition to all possible states Φ_l [2]:

$$\frac{d\sigma_{diff}}{d^2b} = \sum_l \langle \Psi_0|T|\Phi_l\rangle \langle \Phi_l|T|\Psi_0\rangle = \langle \Psi_0|T^2|\Psi_0\rangle = \langle T^2(b)\rangle \,.$$

All of this has been calculated using that only the projectile proton has a substructure. If both the projectile and the target have a substructure, then there can be a single excitation of either the target or the projectile, or that both become excited. Using that the total cross section is $\frac{d\sigma_{tot}}{d^2b} = \langle 2T(b)\rangle_{p,t}$ [2], where the subscript p and t represents that it has been averaged over the projectile and target states, the non-diffractive cross section then becomes [2]:

$$\frac{d\sigma_{non-diff}}{d^2b} = \frac{d\sigma_{tot}}{d^2b} - \frac{d\sigma_{diff}}{d^2b} = \langle 2T(b) - T^2(b)\rangle_{p,t} \,.$$

The remaining cross sections, single and double diffractive are [2]:

$$\frac{d\sigma_{target}}{d^2b} = \langle\langle T(b)\rangle_p^2\rangle_t - \langle T(b)\rangle_{p,t}^2 \,.$$

$$\frac{d\sigma_{projectile}}{d^2b} = \langle\langle T(b)\rangle_t^2\rangle_p - \langle T(b)\rangle_{p,t}^2 \,.$$

$$\frac{d\sigma_{Double}}{d^2b} = \langle T^2(b)\rangle_{p,t} - \langle\langle T(b)\rangle_p^2\rangle_t - \langle\langle T(b)\rangle_t^2\rangle_p + \langle T(b)\rangle_{p,t}^2 \,.$$

These differential cross sections are acquired by averaging, in various order, over the two different sets of states, the states for the projectile, subscript p, and the target, subscript t. The parameters of T can be determined by fitting the integrated expressions above to measured cross sections using PYTHIA8 parametrisations.

T is a parameterisation of the imaginary part of the elastic scattering amplitude. In Angantyr it is defined as the following [2]

$$T(\mathbf{b}, r_p, r_t) = T_0(r_p, r_t)\Theta\left(\frac{r_p + r_t}{\sqrt{2T_0(r_p, r_t)}} - |\mathbf{b}|\right), \tag{11}$$

with T_0 being the opacity of the interaction, which ranges from completely opaque, leading to T_0 having a value of 1, to completely transparent, leading to T_0 having a value of 0. The

r_p,r_t represents the radii of the projectile and target protons, respectively. In the Angantyr parameterization these radii are allowed to fluctuate. The theta function, $\Theta(x)$, takes the value 1 if $x > 0$ and 0 otherwise. T_0 has two definitions, and the physical interpretation of these definitions are essentially opposites. The first definition [2]

$$T_0(r_p, r_t) = (1 - \exp(-\pi(r_p + r_t)^2/\sigma_t))^\alpha, \tag{12}$$

has the physical interpretation that when the size of the proton increases it becomes less transparent. The second definition [2]

$$T_0(r_p, r_t) = (1 - \exp(-\sigma_t/\pi(r_p + r_t)^2))^\alpha, \tag{13}$$

has the opposite meaning, that is, when the proton size decreases it becomes less transparent.

If we take the differential cross section for the non-diffractive case, which is the main concern of this thesis, and integrate away d^2b we are left with just the non-diffractive cross section. The cross section is averaged over all projectile and target states, which is given by the integral over a probability distribution P_p for the projectile and P_t for the target. In Angantyr these probability distributions are given by the same distribution [2]:

$$P(r) = \frac{r^{k-1}e^{-r/r_0}}{\Gamma(k)r_0^k}, \tag{14}$$

where k and r_0 are parameters that are fitted to describe the state, while the state itself is described by r, which can be thought of as the radius of the proton, and Γ is a gamma distribution. With all of this considered, the integrated non-diffractive cross section can be written as

$$\sigma_{non-diff} = \int d^2\mathbf{b} \int dr_p \int dr_t P(r_p)P(r_t)(2T(\mathbf{b}, r_p, r_t) - T^2(\mathbf{b}, r_p, r_t)), \tag{15}$$

with r_p and r_t being the radii of the colliding hadrons, that fluctuate according to the probability distribution above, with $\mathbf{b}$ being the impact parameter. This equation is an all event average.

3 The Angantyr Overlap

It should be clarified before explaining the new overlap function that Angantyr currently does have a method for calculating the overlap [2]. However, it is a very simplified version that equates the explicit impact parameter calculated in Angantyr to the implicit impact parameter used in PYTHIA8. This calculation is modified by a "fudge" factor, which is tuned to data to give a good description of minimum bias final states. Due to the simplified nature of this calculation, it was decided to include an alternative, less naive picture of the overlap function.

As mentioned in the previous section, the non-diffractive cross section of two colliding protons, according to the Good-Walker formalism is

$$\sigma_{non-diff} = \int d^2\mathbf{b} \int dr_p \int dr_t P(r_p)P(r_t)(2T(\mathbf{b}, r_p, r_t) - T^2(\mathbf{b}, r_p, r_t)).$$

Note that Angantyr specifies the impact parameter, as well as the radii of the two protons as well, which, through eq. (12) or eq. (13) (depending on the definition used), gives us the states of the protons. PYTHIA8 only specifies the impact parameter.

This allows a very useful identification of terms. Considering the denominator of eq. (10):

$$\int 1 - \exp(-k\mathcal{O}(b))d^2b = \sigma_{non-diff},$$

it becomes clear that the following can be used to calculate the new Angantyr overlap function.

$$\begin{aligned}\sigma_{non-diff} = \int d^2\mathbf{b} \int dr_p \int dr_t P(r_p)P(r_t)1 - \exp(-k\mathcal{O}(b, r_p, r_t)) = \\ \int d^2\mathbf{b} \int dr_p \int dr_t P(r_p)P(r_t)2T(\mathbf{b}, r_p, r_t) - T^2(\mathbf{b}, r_p, r_t),\end{aligned} \tag{16}$$

with the addition of the fact that the PYTHIA8 method encodes the states of the protons implicitly in the equation, while Angantyr explicitly depends on them, leading to the slight change in dependencies above. Eq. (16) is an all event average, however after this step in the calculation the probability distributions are removed, because the following equality is for only one event.

We then wish to equate the exponent with some expression, as the exponent in the denominator is the numerator of eq. (10). This can be done by taking the natural logarithm of both sides, and changing sign

$$k\mathcal{O}(b, r_p, r_t) = -\log(1 - 2T_0(r_p, r_t) + T_0^2(r_p, r_t))\Theta\left(\frac{r_p + r_t}{\sqrt{2T_0(r_p, r_t)}} - |\mathbf{b}|\right), \tag{17}$$

Which simplifies to

$$k\mathcal{O}(b, r_p, r_t) = -2\log(1 - T_0(r_p, r_t))\Theta\left(\frac{r_p + r_t}{\sqrt{2T_0(r_p, r_t)}} - |\mathbf{b}|\right), \tag{18}$$

This leaves us with an expression for both σ_{hard} and $\sigma_{non-diff}$, and therefore, an expression for $\langle n \rangle$, and we have the following expression for the average number of parton-parton interactions in a hadron collision event.

$$\langle n(b, r_p, r_t) \rangle = \frac{-2\log(1 - T_0(r_p, r_t))}{2T(b) - T^2(b)}\Theta\left(\frac{r_p + r_t}{\sqrt{2T_0(r_p, r_t)}} - |\mathbf{b}|\right), \tag{19}$$

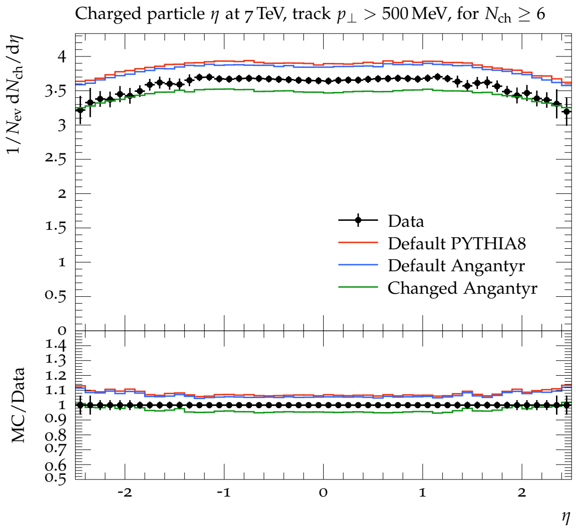
4 Comparison with Experimental Data

The new overlap function described in eq. (19) was implemented as a method to calculate the average number of parton-parton interactions in PYTHIA8. This new method was compared to data, as well as with native PYTHIA8. This comparison was done on data from a minimum-bias measurement done at ATLAS at energies of 900 GeV and 7 Tev [4] where the number of charged particles was measured, as well as the pseudorapidity, η, and $p_{\perp}$ of the particles. It should be mentioned that the measurement is made at *minimum* bias, not *no* bias, and that the results that are presented below show events with at least 6 charged particles with a $p_{\perp}$ of more than 500 MeV. This is because these types events are more likely to be non-diffractive, which is what this thesis is concerned with. The simulations were run with the full minimum bias settings, including diffractive events. The data was collected and afterwards was compiled into the graphs below using a program called Rivet [9].

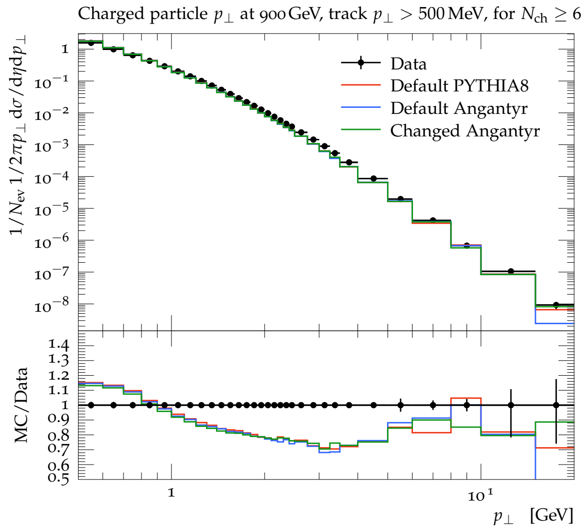
Figure 2 shows the comparison between default PYTHIA8, default Angantyr, and Angantyr using the new overlap function for the non-diffractive cross section, represented by red, blue and green lines respectively. This was done in order to investigate the differences between default Angantyr and Changed Angantyr, with the minimum bias data [4] and default PYTHIA8 as references. Figure 2a shows that the η distribution is lower than PYTHIA8, but as close to data as PYTHIA. Figure 2b shows that the spectra are almost identical between the default PYTHIA8 method and the new overlap method. Figure 2c however, shows that there are some differences compared to data regarding the number of charged particles in the region of $N_{ch} = 15$ to $N_{ch} = 30$, after which the new overlap seems to give a far too large value compared to data. This could be an indication that the fluctuations of the proton radii in the new overlap function are too large.

In Figure 3 we compare PYTHIA8 and the two forms of T_0, defined in eq. (12) and eq. (13). These three cases are defined, respectively, as default PYTHIA8, Changed Angantyr, and Changed Collision Model and are coloured red, blue and green, respectively. This was done in order to investigate which definition of the opacity was better suited to explain data. Similar to figure 2, figure 3 shows that the second definition of T_0 correlates almost exactly with the new overlap function and quite well to default PYTHIA8. In subfigure (c) we can see that the second definition of T_0 leads to a deviation away from the Changed line and approaching default PYTHIA8, settling about halfway in between the two, as well as being closer to data than either, showing that the second definition seems to be more suitable to use in these simulations. However, since this was done before parameters were retuned this might be a premature conclusion.

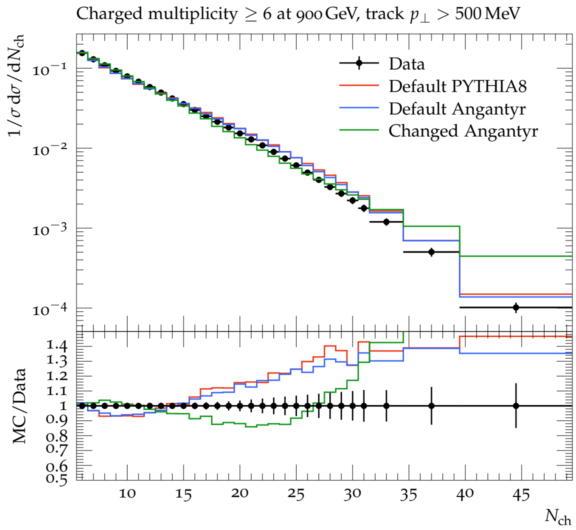
Figure 4 requires some further explanation regarding what ecmPow represents. EcmPow scales the $p_{\perp 0}$, according to eq. (6), where ecmPow is the value 0.215, and this is related to the increase of the total cross section. Figure 4 compares default PYTHIA8, default



(a)

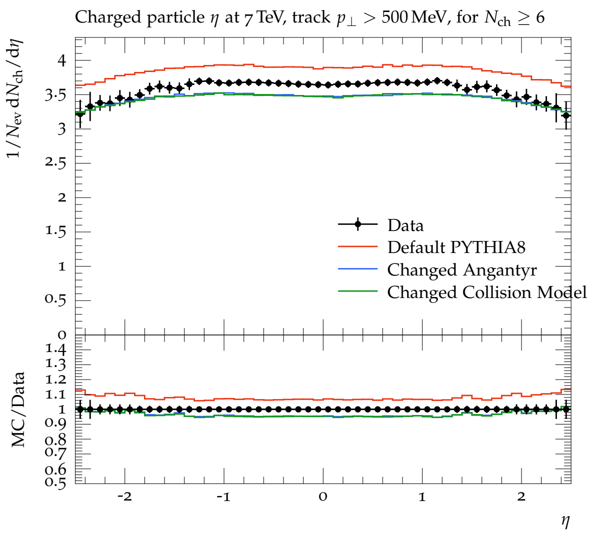


(b)

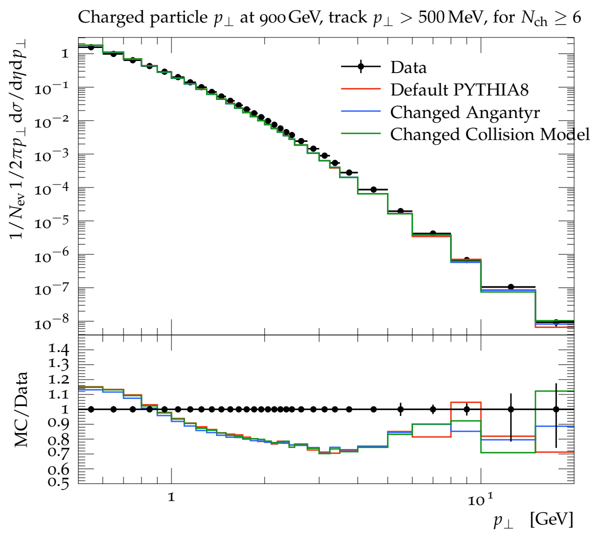


(c)

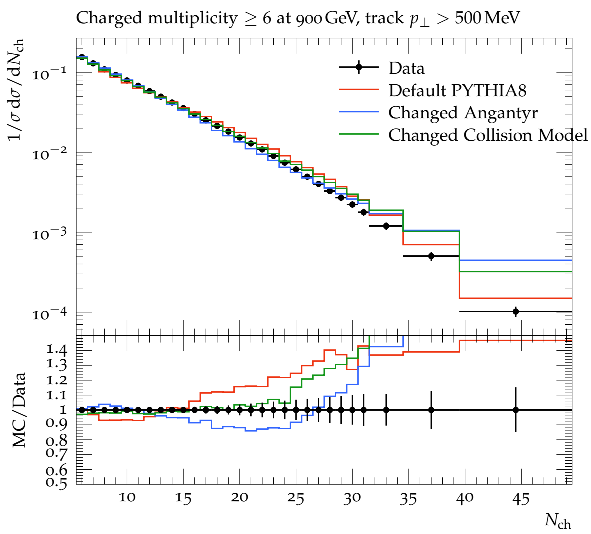
Figure 2: Subfigure (a) shows, per event, the average number of charged particles per unit η, with regards to the η distribution. Subfigure (b) shows the average number of particles per event with regards to the $p_\perp$ distribution. Subfigure (c) shows the relative probability of having a certain number of charged particles be created in the event. The data that is compared to is minimum bias data gathered by ATLAS [4]. The red line represents the default PYTHIA8 [1] event generator. The blue line represents the default Angantyr [2], using the old method of calculating the overlap. The green line represents Angantyr using the new overlap function for the non-diffractive cross section that was calculated in section 4, which will be referred to as Changed Angantyr from now on.



(a)

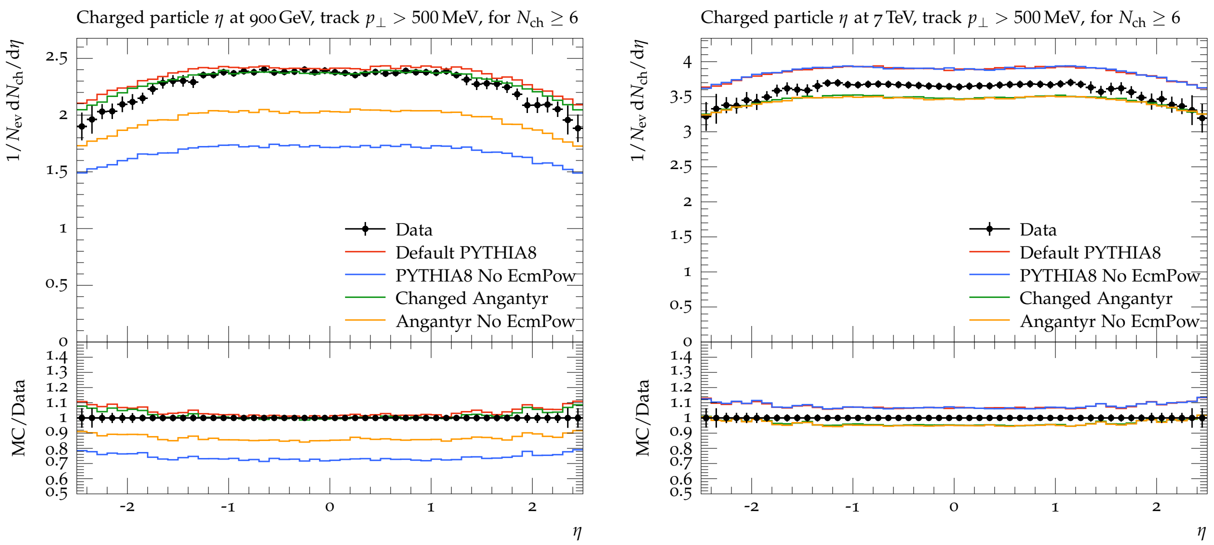


(b)



(c)

Figure 3: The subfigures here display the same distributions as in figure 2. The red line still represents default PYTHIA8 [1]. The blue line represents Changed Angantyr. The green line represents Changed Angantyr that uses the second definition of the opacity, T_0, found in eq. (13), called Changed Collision Model.



(a) (b)

Figure 4: The subfigures here only show two sets of η distribution, similar to figure 2a and 3a. The red line still represents default PYTHIA8 [1]. The blue represents default PYTHIA8 with the parameter MultipartonInteractions:ecmPow set to zero. The green line represents Changed Angantyr. The yellow line represents Changed Angantyr with MultipartonInteractions:ecmPow set to zero. The difference between subfigure (a) and (b) is that subfigure (a) is simulated at 900 GeV, while (b) is simulated at 7 TeV.

PYTHIA8 with ecmPow set to zero, Changed Angatyr and Changed Angantyr with ecmPow set to zero, represented as red, blue, green and yellow lines respectively. This is done to investigate the dependence of the Changed Angantyr model on the ecmPow parameter, and to discover to what extent the Changed Angantyr model compensates for the change in activity. Angantyr compensates for the change because the new overlap have an implicit dependence on the center of mass energy [2] since the parameters that govern the fluctuations are fitted to the cross sections at any given center of mass energy. This is done by fixing the $p_{\perp min}$ at the value used at 7 TeV and then compare what the effect this has on the 900 GeV case, both for default PYTHIA8 and the Changed Angantyr. As can be seen, in figure 4b, at 7 TeV, both the default models (red and green line) are the same as the models with ecmPow set to 0 (blue and yellow line), as expected. In figure 4a it is clear that the difference between the Changed Angantyr and it corresponding zero ecmPow case is less than the difference between default PYTHIA8 and its corresponding zero ecmPow. Of note is that while the Changed Angantyr is better than default PYTHIA8 at compensating for the energy dependence, it is far from perfect.

5 Discussion

The results show that the Changed Angantyr model, while not a bad model, is not as good at reproducing the data as default PYTHIA8. However, PYTHIA8 has many parameters that all have been specifically tuned [10] for the default PYTHIA8 overlap function. Unsurprisingly, when using an untuned overlap function the data is not going to be reproduced as well as with a function that has tuned parameters. In an effort to see if this overlap function can be viably tuned using these parameters, we investigated the effects of changing some of them slightly, and the graphs for those simulations can be found in appendix A.

Despite giving a fairly good description of the data, the new overlap function produced in eq. (19) seems very unintuitive. While it says that the average number of multiparton interactions is dependent on the impact parameter, the only dependence is contained in the theta function, where it determines whether there is a probability of a collision at all. The reason for this is due to the way that Angantyr has defined the T [2]. This runs counter to intuition which says that given two uniform discs, their overlap function should be dependent in some way on the actual geometric overlap. This leaves us with the option to more accurately tune T_0 as well as the shape of the probability distributions, P_p and P_t, or alternatively, change the form of T_0 into something more intuitive so that it is also dependent on the impact parameter. This is more difficult as the parametrisation of T becomes more cumbersome.

Initially, the idea was to derive an overlap function entirely from a geometrical argument. The geometrical argument can be seen in figure 5, where two Lorentz contracted discs collide with some impact parameter b. This leads to three cases. Firstly, where the discs do not impact, when $r_t + r_p < b$, which was uninteresting as PYTHIA8 requires at least one event [1]. Secondly, when one disc is entirely contained within the other, $r_t - r_p > b$, in which case the overlap is simply the area of the smaller disc. The third case, when $r_t + r_p < b$, is the most complex case.

Using several trigonometric identities it is possible to get the following, somewhat complicated, formula to calculate the overlap

$$\mathcal{O}_3 = A_{tot} = r_t^2 arccos\Big(\frac{b}{2r_t} - \frac{r_p^2}{2br_t} + \frac{r_t}{2b}\Big) + r_p^2 arccos\Big(\frac{b}{2r_p} + \frac{r_p}{2b} - \frac{r_t^2}{2br_p}\Big) -$$
$$-\frac{1}{2}\sqrt{(-b + r_p + r_t)(b + r_p - r_t)(b - r_p + r_t)(b + r_p + r_t)}$$

This entirely geometrical picture turned out to be a too naive, and was therefore replaced with the calculations in section 3. This could still be useful if the decision was made to go from the current factorization of T to a different one, where T_0 was not independent in regards to impact parameter.

6 Conclusion

The purpose of this thesis was to implement an alternative method to calculate the overlap into PYTHIA8 that was explicitly dependent on the impact parameter to determine its impact on the average number of multiparton interactions. This new overlap function was calculated using the formalisms used by Angantyr model [2], and by identifying appropriate terms in the overlap function that PYTHIA8 used. Using this new overlap function, simulations were run to compare the new overlap to default PYTHIA8 and default Angantyr.

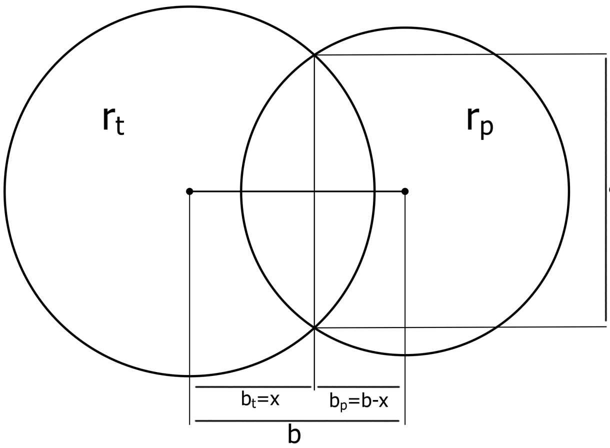


Figure 5: Two discs with radii r_t and r_p whose centers are a distance b away from each other.

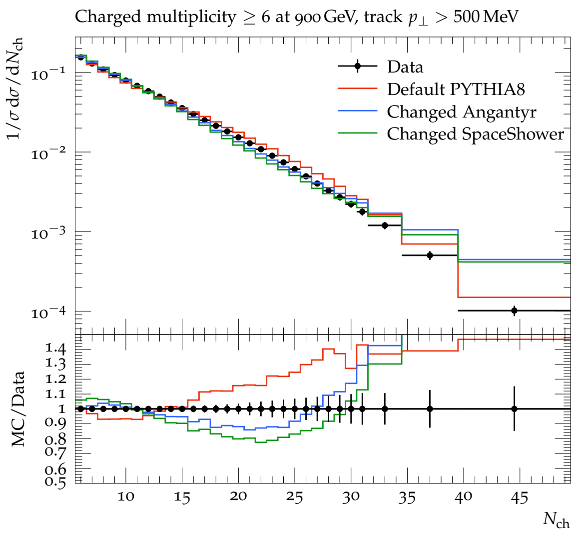
The results enables us to be cautiously optimistic in further developing the overlap function. It seems possible to interpret the Angantyr method of generating proton-proton collisions in terms of an overlap function that can be utilized by PYTHIA8. The overlap function that has been derived in this thesis can be now further tuned in the same way that the other overlap functions that already exist as options in PYTHIA8 have been.

The investigation and results of the different definitions of T_0 are also useful in further development of this overlap function. it was shown that the second definition, found in eq. (13), was more correlated to data, but not by much. It was also discovered that the current factorization of T is unintuitive, having no dependence on the impact parameter beyond informing if there is an impact or not. Both of these results are important moving forward, as they can be used to decide whether to continue to use the second definition of the T_0, or to change the definition to something that is dependent on the impact parameter in a more meaningful way.

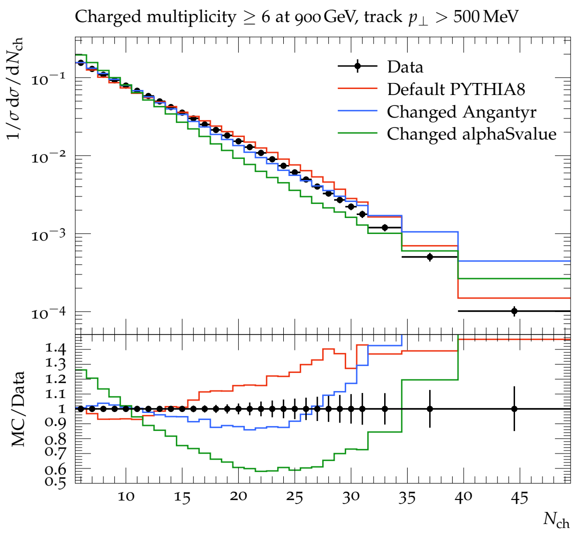
Figure 4 shows an interesting results in regards to the energy dependence. It is clear that the Changed Angantyr method "catches" some of the energy dependence that PYTHIA8 catches using the energy evolution of the soft suppression parameter $p_{\perp 0}$. This is due to the way Angantyr fits its parameters to the different cross sections. Since these cross sections are based on the center of mass energy, this method "catches" some of this energy dependence. However, while it is better than default PYTHIA8, it is still far from perfect.

7 Appendix A

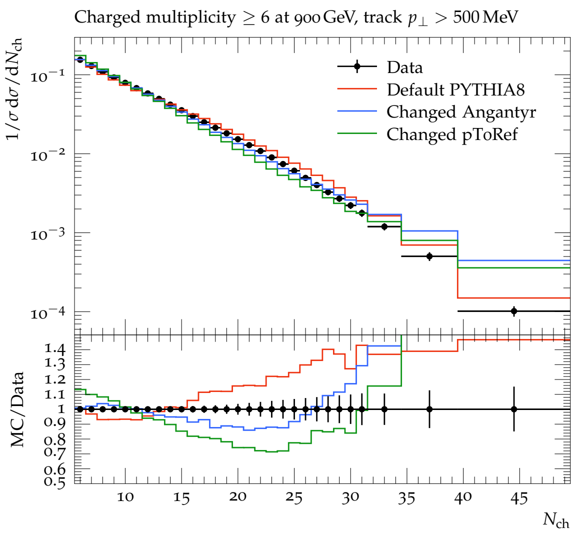
The parameters that were altered were called SpaceShower:alphaSvalue (figure 6a) that had a default value of 0.1365, that was changed to the value 0.12, MultipartonInteractions:alphaSvalue (figure 6b) that had a default value of 0.130, that was changed to the value 0.12, and MultipartonInteractions:pT0Ref (figure 6c) that had a default value of 2.28, that was changed to the value 2.5, and can be seen, respectively, in the figure below. These changed parameters imply that there is a good possibility to be able to tune these parameters to better fit data.



(a)



(b)



(c)

Figure 6

References

[1] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. PYTHIA 6.4 Physics and Manual. *JHEP*, 05:026, 2006.

[2] Christian Bierlich, Gösta Gustafson, Leif Lönnblad, and Harsh Shah. The Angantyr model for Heavy-Ion Collisions in PYTHIA8. *JHEP*, 10:134, 2018.

[3] Torbjörn Sjöstrand. *The Development of MPI Modeling in Pythia*, volume 29, pages 191–225. 2019.

[4] G. Aad et al. Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC. *New J. Phys.*, 13:053033, 2011.

[5] Christian Bierlich, Gösta Gustafson, and Leif Lönnblad. Diffractive and non-diffractive wounded nucleons and final states in pA collisions. *JHEP*, 10:139, 2016.

[6] R.J. Glauber. Cross-sections in deuterium at high-energies. *Phys. Rev.*, 100:242–248, 1955.

[7] M.L. Good and W.D. Walker. Diffraction disssociation of beam particles. *Phys. Rev.*, 120:1857–1860, 1960.

[8] Torbjorn Sjostrand and Maria van Zijl. A Multiple Interaction Model for the Event Structure in Hadron Collisions. *Phys. Rev. D*, 36:2019, 1987.

[9] Christian Bierlich et al. Robust Independent Validation of Experiment and Theory: Rivet version 3. *SciPost Phys.*, 8:026, 2020.

[10] Peter Skands, Stefano Carrazza, and Juan Rojo. Tuning PYTHIA 8.1: the Monash 2013 Tune. *Eur. Phys. J. C*, 74(8):3024, 2014.