Analysis of Monte Carlo Simulation for Low-Energy Drell-Yan Process

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Abstract: Analysis code was written for a Drell-Yan measurement at $\sqrt{s} = 40 \ GeV$, and the measurements were compared to the predictions from PYTHIA 8. The predictions were studied as a function of the primordial k_T and parton shower. A good agreement between the Monte Carlo prediction and experimental data was found at $\sigma_{kT} = 1.0 \ GeV$ and with initial state radiation of the partons turned on. Finally, predictions were generated using different Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs) in the CASCADE Monte Carlo generator, and the best PDF setting was determined to be PDF 3, which corresponds to $\sigma_{kT} = 0.5 \ GeV$.

1 Introduction

Drell-Yan process is a quark-antiquark annihilation process which produce a virtual photon or a Z-boson that in turn decays into a lepton-antilepton pair. The virtual photon produced here is time-like. In this analysis, the exchanged particle is dominantly a virtual photon, since we consider the process at low energies, around 40 GeV. The kinematic variables Feynman-x (x_F), dilepton mass ($M_{l^+l^-}$) and transverse momentum (p_T) of the dileptons are significant in order to perform the analyses. Monte Carlo simulations can be generated using a generator like PYTHIA[1], and analysed alongside experimental data to verify the reliability of the predictions.

2 Theory

The Drell-Yan process is characterised by quark-antiquark annihilation into a final state lepton-antilepton pair. The four-momentum of this pair corresponds to the four-momentum of the exchanged particle, thus giving information about the type of the exchanged particle. At low energies, the process is dominated by the exchange of a virtual photon (a photon of high mass), whereas at higher energies, it is dominated by the exchange of a Z-boson. A Feynman diagram of the Drell-Yan process is shown in figure 1.

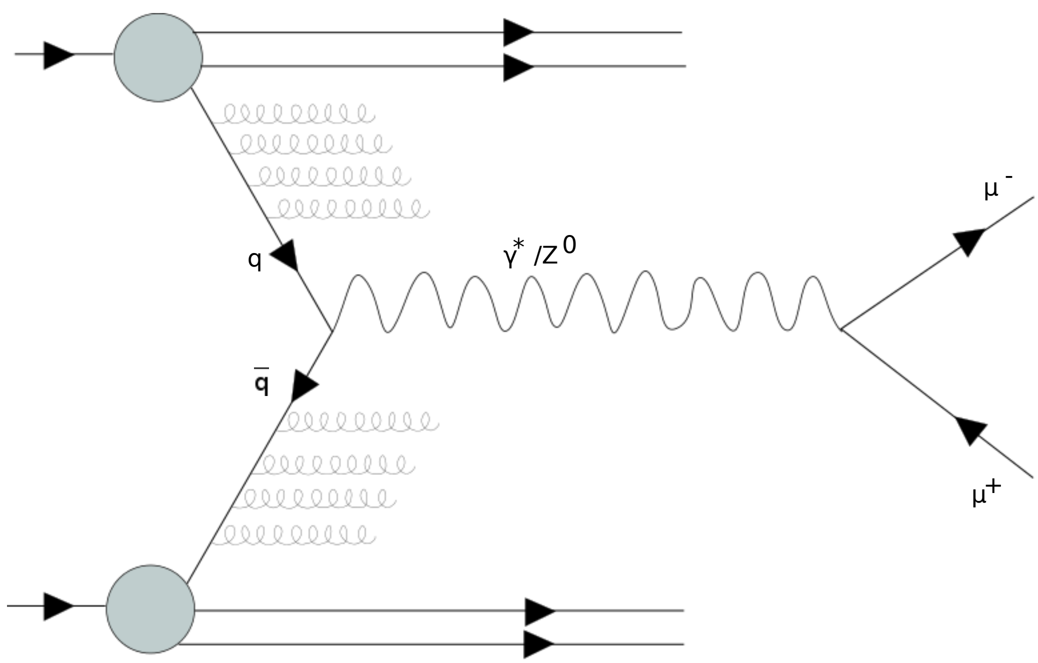

Figure 1: *Feynman diagram of the Drell-Yan process. Two partons (quarks) annihilate to produce a γ^* or Z^0 that decyas into l^+ and l^-. Gluons may be radiated from the partons before they collide.*

The Drell-Yan process is important for studying the parton distribution functions (PDFs) within the hadrons that contribute the initial quark-antiquark pair. PDFs depend on various factors, such as the energy of the hadrons (E), transverse momenta (p_T), longitudinal momentum fractions (p_l), etc. They give the probability of a quark from one hadron colliding with an antiquark from the second hadron. Information about the PDFs can be derived from analysing these kinematic properties, and this information is important in studying high-energy processes.

2.1 Dilepton Mass and Feynman-x

The momentum transfer in the process is expressed by the variable q^2. It is equal to the square of the final-state dilepton mass. This value is proportional to the parton momentum fractions[2].

$$M^2 = sx_1x_2 \tag{1}$$

where s is the centre-of-mass energy of the collision, and x_1 and x_2 are the momentum fraction of the partons. x_1 and x_2 are not directly accessible for measurement. However, they are related to the ratio of the longitudinal momentum of the dilepton to its maximum value as follows[2].

$$x_1 - x_2 = \frac{p_l}{p_l^{max}} = x_F \tag{2}$$

where

$$p_l^{max} \approx \frac{\sqrt{s}}{2} \tag{3}$$

Here, x_F is called Feynman-x. Thus, by choosing the proper value of x_F, we can choose the final-state particles with desired masses.

The x_F can lie between -1 and 1, depending on how the total longitudinal momentum is divided between the hadronic beams involved in the collision. If the two beams are exactly equal in their four-momenta and in opposite directions, x_F would be 0. The x_F value gives the direction of boost of the final dileptons.

The transverse momentum p_T is a good indicator of parton evolution in the process, because a larger number of the dileptons at higher p_T hints at a larger contribution from gluon radiation (see figure 1). The dilepton mass gives the mass of the exchanged particle.

2.2 Primordial k_T and Parton Shower

Primordial k_T refers to the intrinsic transverse momentum of the interacting partons, that contribute to the p_T of the final dileptons. This is one parameter that could play a considerable role in the fine-tuning of our predictions. The contribution of primordial k_T is represented as the combined contributions of two factors called the hard k_T and the soft k_T. These can be represented as two overlapping Gaussian functions, as in figure 2.

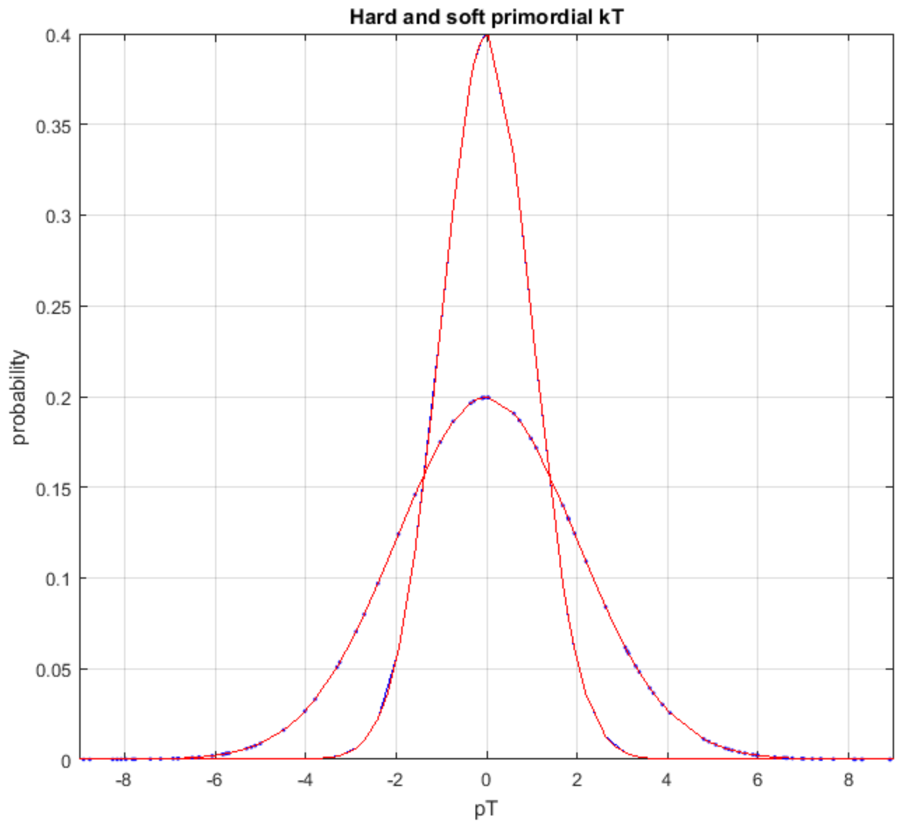

Figure 2: *The Gaussian functions for soft and hard k_T. the combined contribution of both curves determine the total primordial k_T contribution to the process.*

The soft k_T dominates in the lower p_T region, around 1 GeV, whereas the hard k_T dominates in the higher p_T region, around 2 GeV. In PYTHIA 8, the Monte Carlo generator that was used in this analysis, the default values of soft and hard k_T are set to 0.9 GeV and 1.8 GeV, respectively.

Another factor that affects the final state p_T is the parton shower. This is the radiation that is emitted from the partons involved in a high energy process. Parton showers are also divided into two, namely initial state radiation (ISR) and final state radiation (FSR). ISR in a Drell-Yan process is the radiation of gluons from the partons that collide, shown in figure 3.

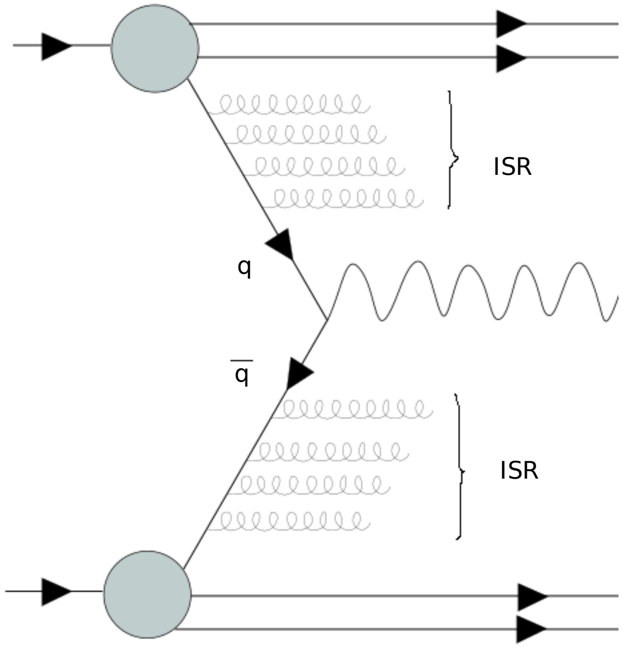

Figure 3: *Parton shower. Showers of gluons from the initial partons is called the initial state radiation (ISR).*

FSR is the photon radiation from the final state leptons. However, in the case of a muon-antimuon pair in the final state, the FSR is negligible, since the muon radiation is QED, which we did not want to consider.

3 Project Motivation and Methodology

The aim of the project was to code an analysis routine[3] for Drell-Yan process with a muon-antimuon pair as the final state particles, for the measurement of the experiment Fermilab E866/NuSea. The data was was obtained from the thesis "Measurement of Continuum Dimuon Production in 800-GeV/C Proton-Nucleon Collisions (J.Webb)"[2]. It is a fixed-target experiment with the centre-of-mass energy (E_{com}) around 40 GeV. The low E_{com} means that the mass of the exchanged particle lies in the region dominated by the virtual photon and has negligible probability of being a $Z-$boson. The experimental data was in the dimuon mass range between 4.2 GeV and 16.85 GeV, so as to avoid the resonance peaks. The dimuons were also within an x_F range between -0.05 and 0.15, and distributed into different histograms (p_T vs probability) based on $M_{\mu^+\mu^-}$. After the Monte Carlo predictions were generated, they were compared with the experimental data. The predictions were plotted in the same histogram as the measurement points to compare the accuracy of the predictions. Afterwards, it was attempted to improve the predictions by adjusting various parameters in the steering file for the event generation.

4 Analyses and Comparison

First, a series of histograms for various intervals of $M_{\mu^+\mu^-}$ were generated with the Monte Carlo generator PYTHIA. This was used as the reference for future optimisations. A reference histogram in the dimuon mass interval between 6.20 GeV and 7.20 GeV can be seen in figure 4(left).

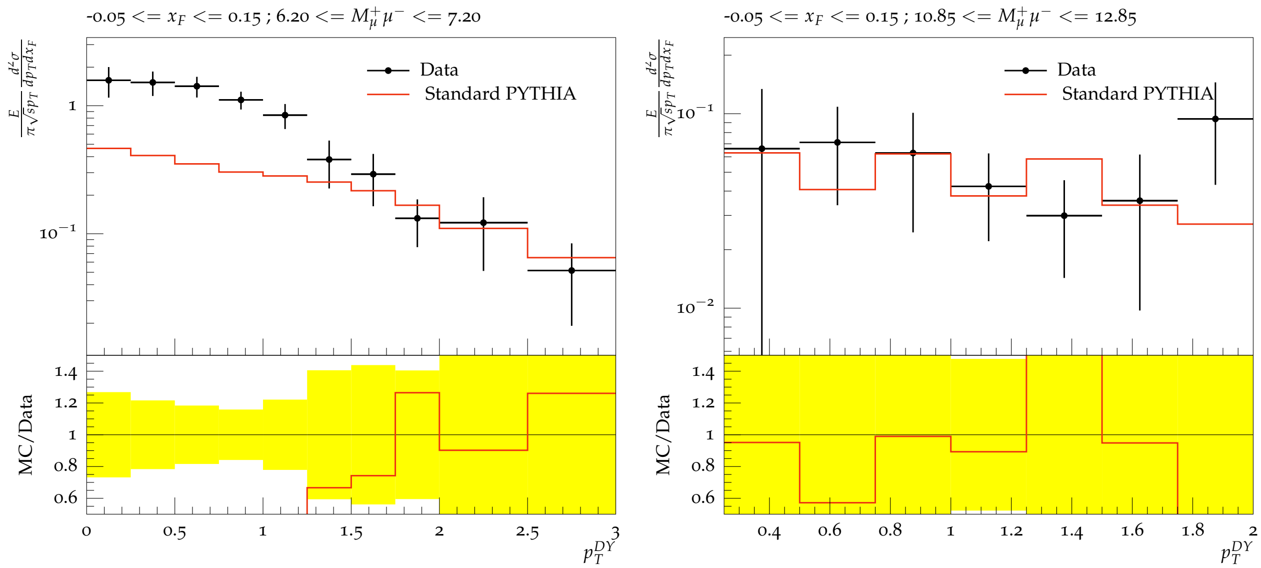

Figure 4: *Reference histograms. The p_T vs Probability histogram for standard PYTHIA settings in the middle (left) and towards the higher end (right) of the of the $M_{\mu^+\mu^-}$ interval analysed.*

This mass interval was chosen because it was approximately in the middle of the chosen $M_{\mu^+\mu^-}$ range and showed the probability trends of different p_T values clearly. In the intervals closer to the upper limit, the statistics of the measurement was too poor to draw conclusions. This is seen in figure 4(right). A disagreement between the prediction and the theory can be observed in the low p_T region. The first parameter to be adjusted to improve the accuracy of the prediction was the primordial k_T. For this, the k_T contribution was varied. Multiple runs were performed with different values of k_T. As seen from the figure 5(left), a primordial k_T value (represented by σ_{kT}) of 1.0 GeV gives the best agreement in the low p_T region. However, now there is a large divergence in the higher p_T region. In a higher mass interval, as expected from the reference histograms, the effects are harder to evaluate (figure 5(right)).

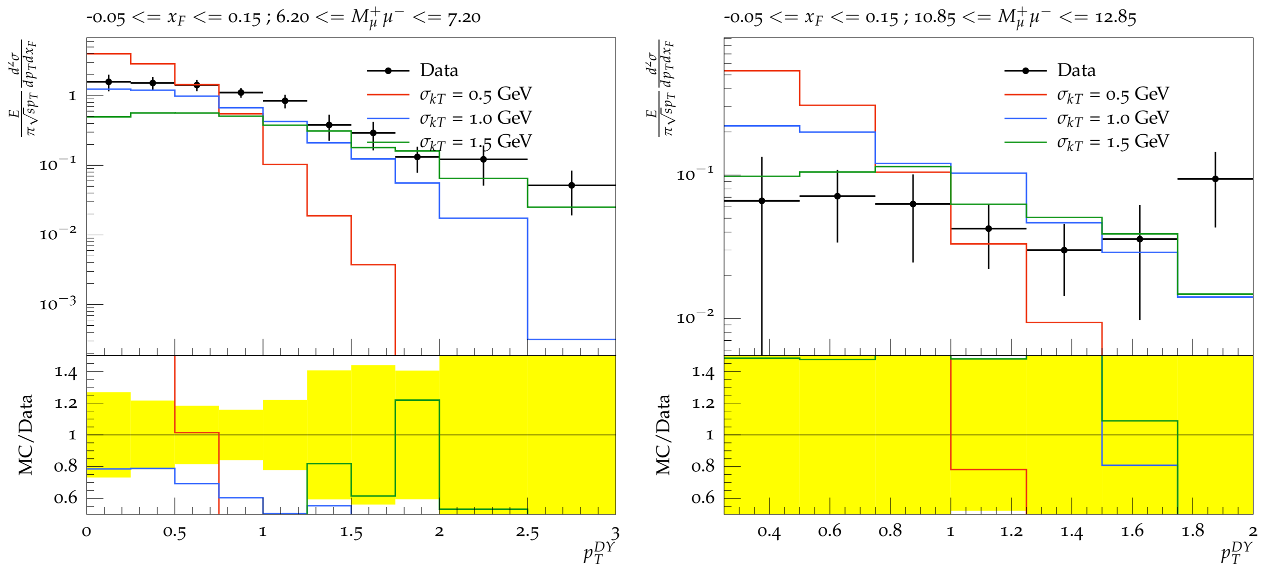

Figure 5: *Contribution of primordial k_T. The p_T vs Probability histogram for varying values of σ_{kT} in the middle (left) and towards the higher end (right) of the of the $M_{\mu^+\mu^-}$ interval analysed.*

The difference of the prediction to the data at higher p_T can be explained by the parton shower, which was turned off. The FSR was left turned off, because its contribution is negligible for our purpose, as mentioned in theory. The predictions with ISR turned on, but with primordial k_T off can be seen in figure 6.

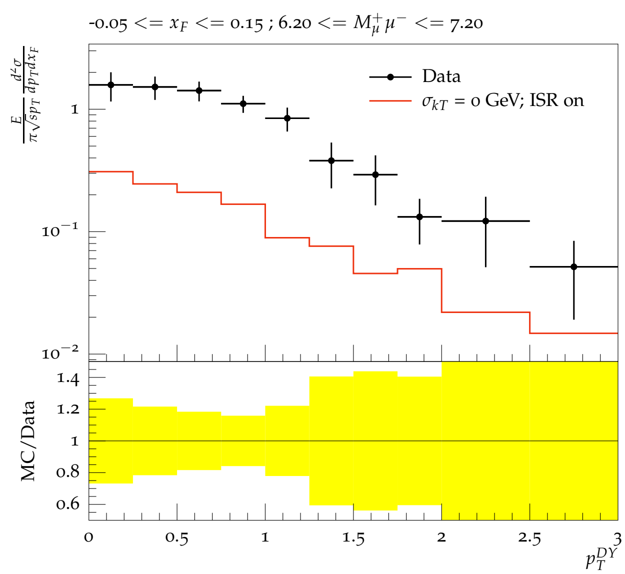

Figure 6: *Effect of parton shower. Although the ISR is turned on, the simulation still disagrees with data.*

The plot is different from the reference, and the predictions show a shape following the data.

Next, primordial k_T as well as ISR were taken into consideration. This gave a satisfactorily good agreement between prediction and data. Figure 7 presents the results with multiple values of σ_{kT}. It can be observed that the plot corresponding to $\sigma_{kT} = 1.0 \;\; GeV$ with ISR turned on shows the best Monte Carlo-data agreement in shape out of the three options.

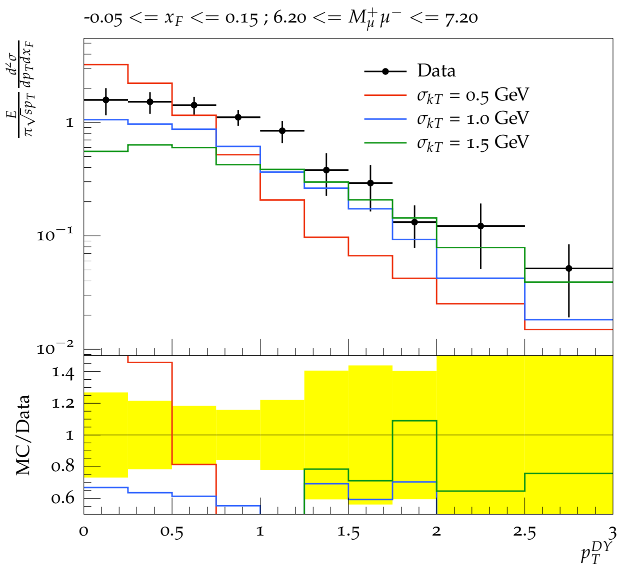

Figure 7: *Contributions from primordial k_T of the partons as well as parton shower. The green plot, with $\sigma_{kT} = 1.0 \;\; GeV$ is the closest to experimental observations.*

Finally, a comparison of results with $\sigma_{kT} = 1.0 \;\; GeV$ with and without ISR can be seen in figure 8.

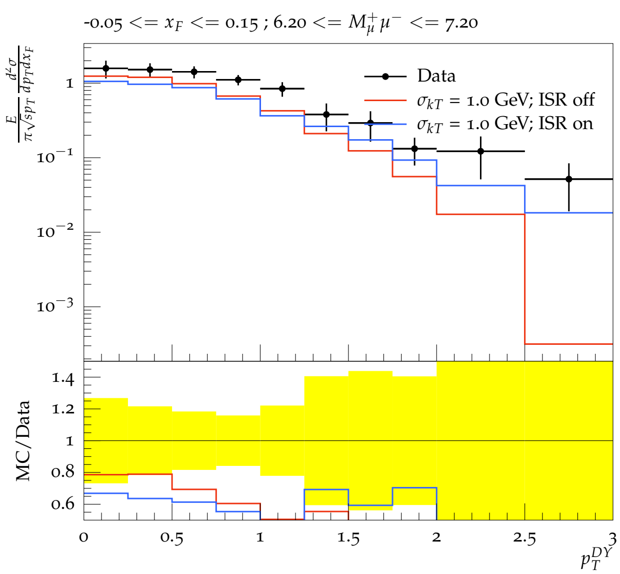

Figure 8: *The p_T vs Probability histogram for standard PYTHIA settings in the middle (left) and towards the higher end (right) of the of the $M_{\mu^+\mu^-}$ interval analysed.*

4.1 CASCADE Tests

The next step in analysis was to use another Monte Carlo generator, CASCADE[4] to perform the tests. CASCADE uses a transverse momentum dependent (TMD) PDF. As explained in the theory section, PDFs define the probability of two partons from the incoming hadrons interacting with each other. TMD PDFs have the intrinsic transverse momentum σ_{kT} of the partons defined within the PDF, so that the settings need not be changed manually every time. The desired TMD PDF can be chosen before the run, which contains all the hard and soft k_T parameters preadjusted. It also has the parton shower taken into account in the default setting, eliminating the necessity to manually turn on the parton shower option for each run. In the CASCADE steering file, three PDF settings are available, each defining the probability of Drell-Yan process with a different σ_{kT}. PDF 1, PDF 2 and PDF 3 correspond to $\sigma_{kT} = 1.5 \;\; GeV$, $\sigma_{kT} = 2 \;\; GeV$ and $\sigma_{kT} = 3 \;\; GeV$, respectively. The rivet routine was run using CASCADE for these three settings to determine the one that gives the closest agreement with data (see figure 9).

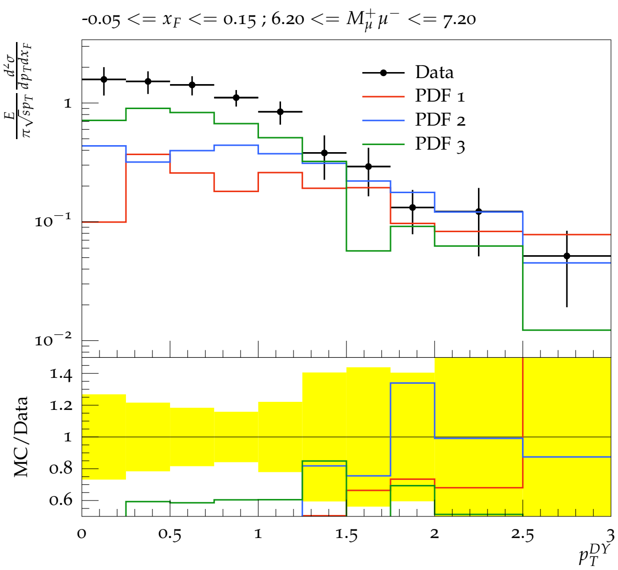

Figure 9: *The predictions using three different TMD PDFs generated using CASCADE. Initial and final state parton showers are on by default.*

For a better estimation, the predictions from PDF 2 and PDF 3 were compared individually with the best PYTHIA settings, as shown in figure 10.

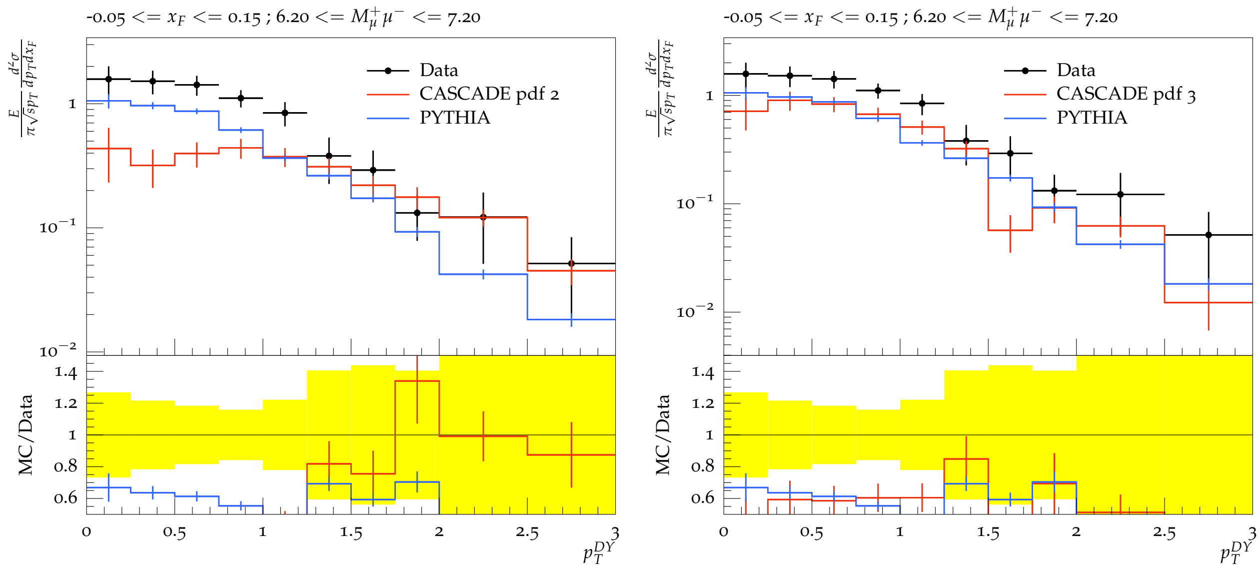

Figure 10: *Comparison of CASCADE predictions with PDF 2 (left) and PDF 3 (right) with the optimised PYTHIA predictions.*

It was thus determined that PDF 3 gave the best agreement with data. As seen from figure 10(right), the analysis using PDF 3 (with $\sigma_{kT} = 0.5\ \ GeV$) in CASCADE was comparable to the predictions from PYTHIA (with $\sigma_{kT} = 1.0\ \ GeV$).

5 Conclusions and Outlook

A rivet plugin to analyse Drell-Yan process at low centre of mass energy was written and predictions were generated using the Monte Carlo generator PYTHIA 8. Various parameters were adjusted: the primordial k_T, which is the intrinsic transverse momentum of the initial partons, shows the most influence in the lower p_T region, whereas parton showers, specifically ISR, shows an influence in the higher p_T region. The best setting from our investigations was an intrinsic transverse momentum σ_{kT} of 1.0 GeV, with ISR included.

Afterwards, CASCADE, another Monte Carlo generator that uses TMD PDFs, was used to generate predictions. There were three PDF options available in CASCADE. From the comparison of the predictions to each other and to the best PYTHIA settings, it was found that PDF 3 in CASCADE was closest in agreement with data. While PYTHIA showed $\sigma_{kT} = 1.0\ \ GeV$ to generate the best predictions, CASCADE predictions were optimised at $\sigma_{kT} = 0.5\ \ GeV$.

The next step would be to generate Monte Carlo predictions with more values of σ_{kT}, especially between 0.5 GeV and 1.0 GeV, to fine-tune the settings.

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