Charged Particle Spectra
In Deep Inelastic ep Scattering

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Abstract

We investigate the Charge Particles Spectra in the spectrum of transverse momentum and peusodorapidity in photon-proton center of mass frame namely, p_T^* and η^* in deep inelastic scattering between an electron and the protron. Then, we compare the simulation by using Monte Carlo generators to the data obtained from HERA at DESY. Moreover, we also look at a high resolution scale Q^2 to investigate the effect of intrinsic transverse momentum of parton k_T^* and parton shower on the Charge Particle Spectrum.

Motivation Scientist has been trying to understand and explain the very fundamental question about nature such as what we are made up, where we came from, where we live in the vast universe. Physics is one of those science, which tries to answer those very crucial questions with various types of topics underlying certain laws of physics. The two cornerstones of the laws of physics are general relativity and quantum physics, which independently work extremely well at different circumstances. General Relativity, the classical field description of gravity, describes the behaviour of objects at large scale such as the universe and galaxies. As a result, we have the standard Big Bang model of the universe which we expect that this would give us the promising answer about where we live, where we came from, and where we will end up. On the other hand, Quantum Physics is the approach where we describe the tiny world of atom and an individual behaviour of particle. Therefore, we classify the classes of elementary particles by standard model of elementary particle physics. Consequently, the standard model of particle physics is the model for describing the interactions and processes in elementary particles such as electrons, neutrinos, quarks etc except gravity.

In this report, we are interested in the use of standard model of elementary particles for an explaination of experimental observations obtained from a particle accelerator collider. As a result, we will simulate events of particle collisions by using Monte Carlo generators to evaluate the charge particle spectra obtained from detectors of the collider. Moreover, we also consider the kinematic parameters and physical explanations for the charge particle spectra. We will also study what physical processes will have an impact on the observed charge particle spectra expecially for the intrinsic transerve momentun of partons and parton shower. Nevertheless, not only do we have a better understanding of how certian known phenomena having an impact on the charge particle spectra, but also look for a new physics at a certian range of energies scale.

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Contents

1 Introduction

Quantum Field Theory is the framework underlying the current understanding of the elementary particles physics where elementary particles arise from the quantization of field responded from such elementary particle. Moreover, the interactions between elementary particles can also be understood by the additional gauge fields quantized as gauge particles, which is the particle exchanged for a certian interaction. As a result, these are called Standard Model. In Standard model, we can classify elementary particles by two groups for different roles. Firstly, fermionic particles are the elementary particle with intrinsic angular momentum or spin of a half-integer, which is governed by the Pauli's exclusion principle. We can also divide these fermions into leptons and quarks, which have different kind of interaction based on the difference of the gauge boson exchange. These fermonic elementary particles make up the ordinary matter. Secondly, gauge-boson particles are the particles having integer intrinsic angular momentum or spin. They are not governed by Pauli's exclusion principle. These particles are responsible for the interactions between the ordinary particle and also between itself depending whether or not which type of charge they carry. The gauge graviton having spin 2 is a mediator between the elementary particles that have a mass charge, which results in the gravitation interaction. The abelian gauge photon having spin 1 is a mediator between the elementary particles that have an electric charge, which results in the electromagnetic interaction. The gauge $\mathcal{Z}$ and $\mathcal{W}^{\pm}$ bosons having spin 1. Finally, the non-abelian gauge gluon having spin 1 is a mediator between the elementary particles that have a color charge, which results in the strong interaction. [1] [2] [3]

1.1 Quantum Chromodynamics

Quantum Chromodynamics is the theory that describes strong interaction between quarks by the existence of gluon as a gauge particle. In strong interaction, gluon will be mediator between the color charge particles like the electrical interaction where photon will be a mediator for electrical charge particles. For example, in electromagnetism an electron with negative charge $-e$ would be a ble to interact with a proton with positive charge $+e$ via the gauge photon. However, the difference between the strong and electromagnetism are that the electromagnetic interaction is abelian gauge theory, while the strong interaction is a non-abelian gauge theory. This indicates that gauge photon does not carry the electrical charge, so photons do not interact with themselves. On the orther hand, the gauge gluon is non-abelian gauge, so these gluons will carry color charge. Then, they would be able to interact among themselves.

1.1.1 Partons

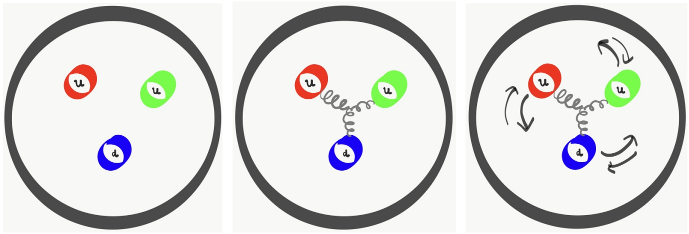

Figure 1: The picture showing the beviour of parton insite proton

In order to understand the behavior of quarks and gluons inside a hardron or meson, we will consider the point-like particles, quarks and gloun, as partons. These partons can be described by parton distribution function $f_i(x, Q^2)$. The parton distribution function indicates the probability of finding a parton of flavor i (quarks or gluon) carring a momentum fraction x of the momentum of proton at an energy scale Q^2 of hard interaction [4]. Moreover, these partons can also jigger around inside the parent's particle, so they would have the intrinsic transerve momentum k_T described by TMD $A(x, k_T^2, Q^2)$.

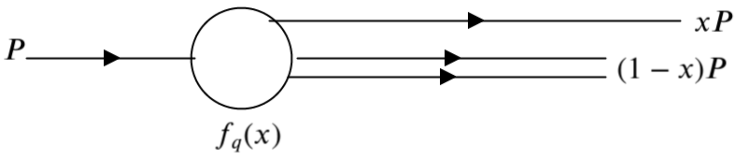

Figure 2: The picture showing the beviour of momentum fraction of parton

1.2 Deep Inelastic Scattering

To have a better understanding of how partons behave, we study the system in which partons live namely hadrons. Here, we will study the behavior of partons by looking at the proton. Normally, when we want to study a system, we will use light or electron to probe the system's characteristcs. For example, physicists use light to study the structure of solid states. Sometimes, biologists also use electron to see the structure of molecule. For high-energy particle physics, we will do a similar proceedure. However, the difference is that the scale at which we are looking is very small, less than $1 fm$. Thereofore, we need a very high energy particle, electron or photon, so that we see the behavior of these partons. As a result, we will collide a beam of electron with a beam of protons, which can be written as the following diagram.

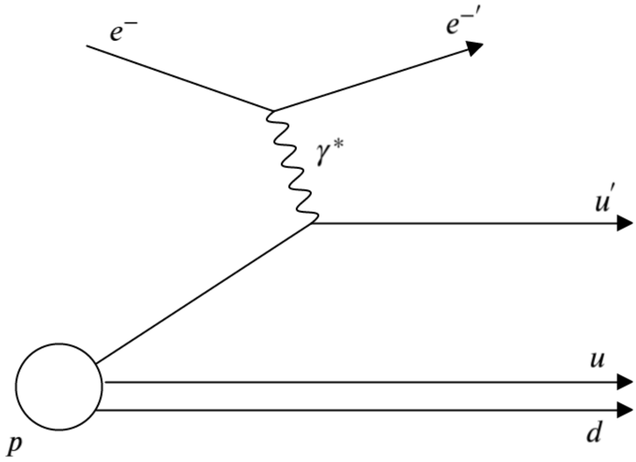

Figure 3: Deep inelastic scattering between an electron and proton

l is the imcoming lepton interacting with quarks inside the proton via photon exchange since they both have electrical charges. l' is the scattered lepton. Therefore, there will be the energy tranfer $q = P_l' - P_l$. Then, we will be able to observe the scattering charge particles, and use it to study physical phenomena or to find a new physics by reconstructing collision events with the simulation of Monte Carlo generators. The diagram written in the previous section is called "Feynman Diagram". The Feynman diagram is used to represent the physical processes in high-energy physics. It is also used to represent the mathematical expression in each vertex in such a diagram. Therefore, it is very crucial in high energy physics that we can have an idea of what is happening in a given diagram. In order to do the calculation of the scattering process, one needs the perturbation theory. The perturbation theory is the theory that we expand some functions in order to make it more simple to handle. Normally, we will focus on only few terms of the expansion of the perturbation. Here, we will consider the leading order of the perturbation and the next leading order which is the second term of the perturbation.

1.3 QCD Phenomenology

When we collide high energy particles, here an electron and proton, there is a lot of physics that happend there. Here, we will consider the phonomena that take place the deep inelastic scattering process. These phenomena will influnce the charge particle spectrum. We now consider these pheonomena.

1.3.1 Parton Shower, QCD Radiation

Parton shower is a phenomenon that partons can radiate gluon as they move. This is similar to the fact that an electron will radiate the electromagnetic wave or photon as it is accelerated. The parton shower can be written in terms of Feynman diagram as the following :

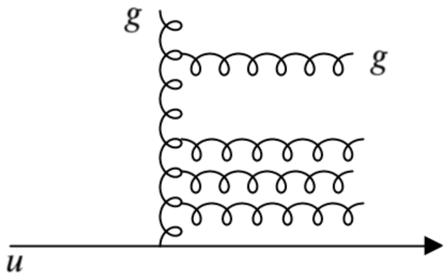

Figure 4: Parton shower, QCD radiation

This phenomena can be understood pretty well in a high transfer momentum Q^2.

1.3.2 Intrinsic transverse momentum k_T

The intrinsic transerve momentum in the scattering process can result from both the jiggering of partons inside the parent's particle and the parton shower. As a result, these partons at the scattering process can have transverse momenta instead of only longitudinal or collinear momenta from the proton's momentum. Let's take a look at how this intrinsic transverse momentum come to play in the labatory frame on the left diagram

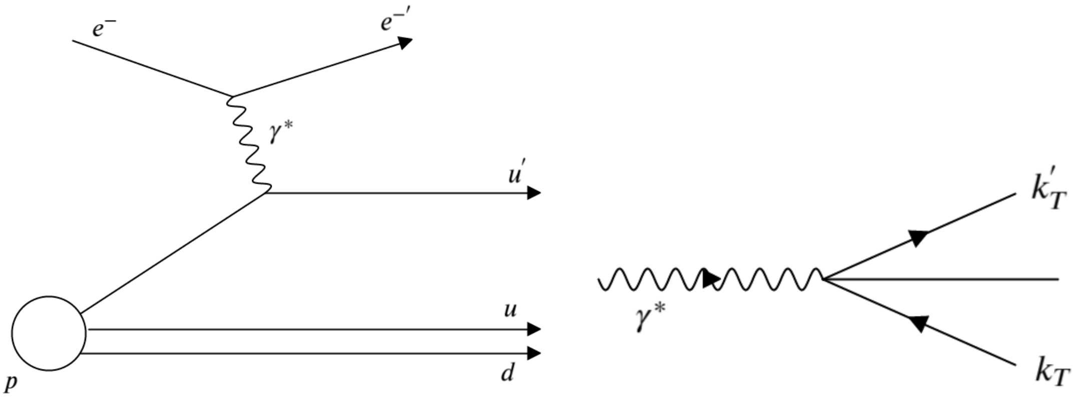

Figure 5: Deep inelastic scattering between an electron and proton in Laboratory frame and photon-proton center of mass frame

We can also look at the photon-proton frame on deep inelastic scattering on the right-hand side diagram.

1.3.3 QCD Fragmentation

Fragmentation or hardonization is a phenomena that the scattered quarks can combine with other quarks resulted from QCD vacuum pair creations to form other mesons or baryons. The fragmentation or hardonization process can be written in Feynman diagram as follows :

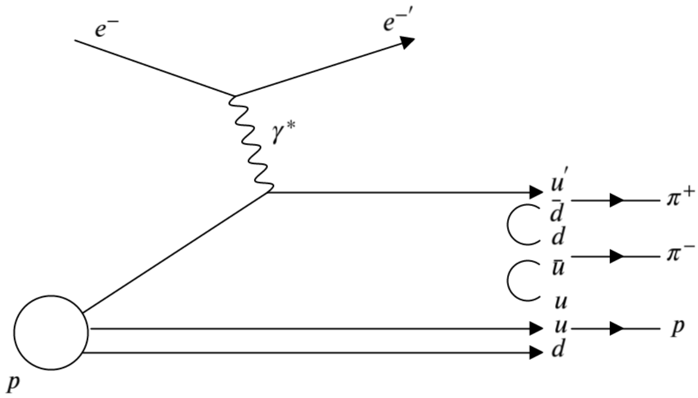

Figure 6: The Fragmemtation

This phenomena is crucial in order to be able to understand the charge particle spectrum.

2 Simulation

Simulation is the way we reconstruct events of the collisions between particles in the particle collider. This would give us better understanding of the physical process, or sometimes we would be able to find a new physical process. The Monte Carlo generators simulation will be proceeded by producing the random number of events as a result the more numbers of event you have, the better statistics would be. Here, we will use RAPGAP and PYTHIA to describe the charge particle spectra.

2.1 Kinematic Parameters

In order to reconstruct events, we need to understand parameters used to desribe the experimental obervations.Then, we use these parameters to our Monte Carlo generators simulation. Here, we will talk about two important parameters so that we can describe and reconstruct the charge particle spectrum in the simulation.

2.1.1 Transverse momentum

Transverse momentum is a very fundamental quantity of particle, so we then will describe the charge particles distribution on transverse momentum spectrum. However, the problem is that we cannot build the detector such that we can measure the longitudinal or collinear momentum parallel to the axis of moving beam particles. Fortunately, we can measure transverse momentum which is a momentum measured transervely respect to the beam of particles which is moving in the horizontally as shown in Figure 7,

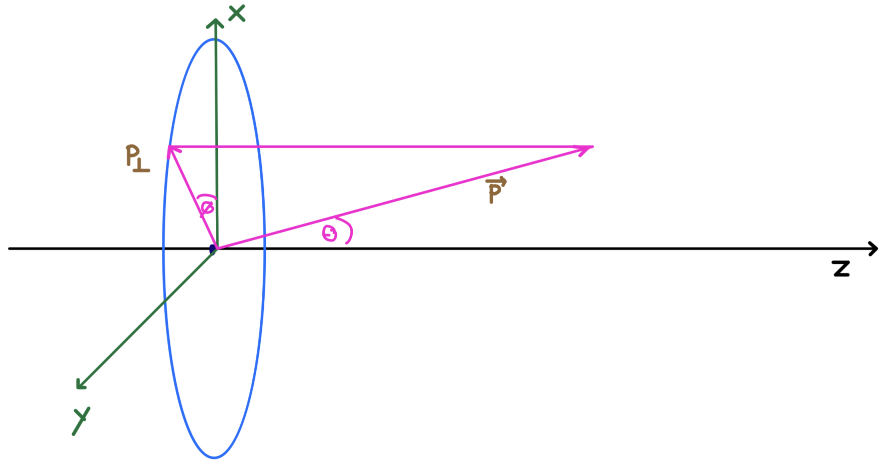

Figure 7: The coordinate showing p_T

where the z axis is the axis of moving beam particles

2.1.2 Pseudorapidity

In the detector, we can also measure the pseudorapidity of each outgoing particle. Then, we will also describe the charged particle distribution in terms of the pseudorapidity spectrum in both the simulation and the experimental observation. The pseudorapidity can be expressed as

$$\eta = -\ln(\tan(\frac{\theta}{2})) \tag{1}$$

where θ is the angle between the moving beam particles with respect to observed particles. Now, we will take a look at the simulation and also comparision to HERA data.

2.2 Comparision with H1 Data

Here, we used the Monte Carlo generators on RAPGAP and PYTHIA to describe the charged particle spectrum between prositon and proton at the energy of $E_{e^+} = 27.6GeV$ and $E_p = 300GeV$ for different Q^2 and x. We will look at the charged particle distribution in photon-proton center of mass frame. [5]

2.2.1 Best Fit Plots

We plotted the charge particles distribution by using Rapgap and Pythia for the p_T spectrum for $0 < \eta^* < 1.5$ and $1.5 < \eta^* < 5.0$ with different range of momentum fraction x and different range of the momentum transfer Q^2. Then, we integrated overall such range of $0.0001 < x < 0.01$ and $5.0 < Q^2 < 100.0 GeV^2$. As a result, one can obtain the charge particle distribution p_T^* spectrum for $0 < \eta^* < 1.5$ and $1.5 < \eta^* < 5.0$. We also have the charge particles distribution in η^* spectrum for $p_T^* < 1.0 GeV$ and $1.0 < p_T^* < 10.0 GeV$

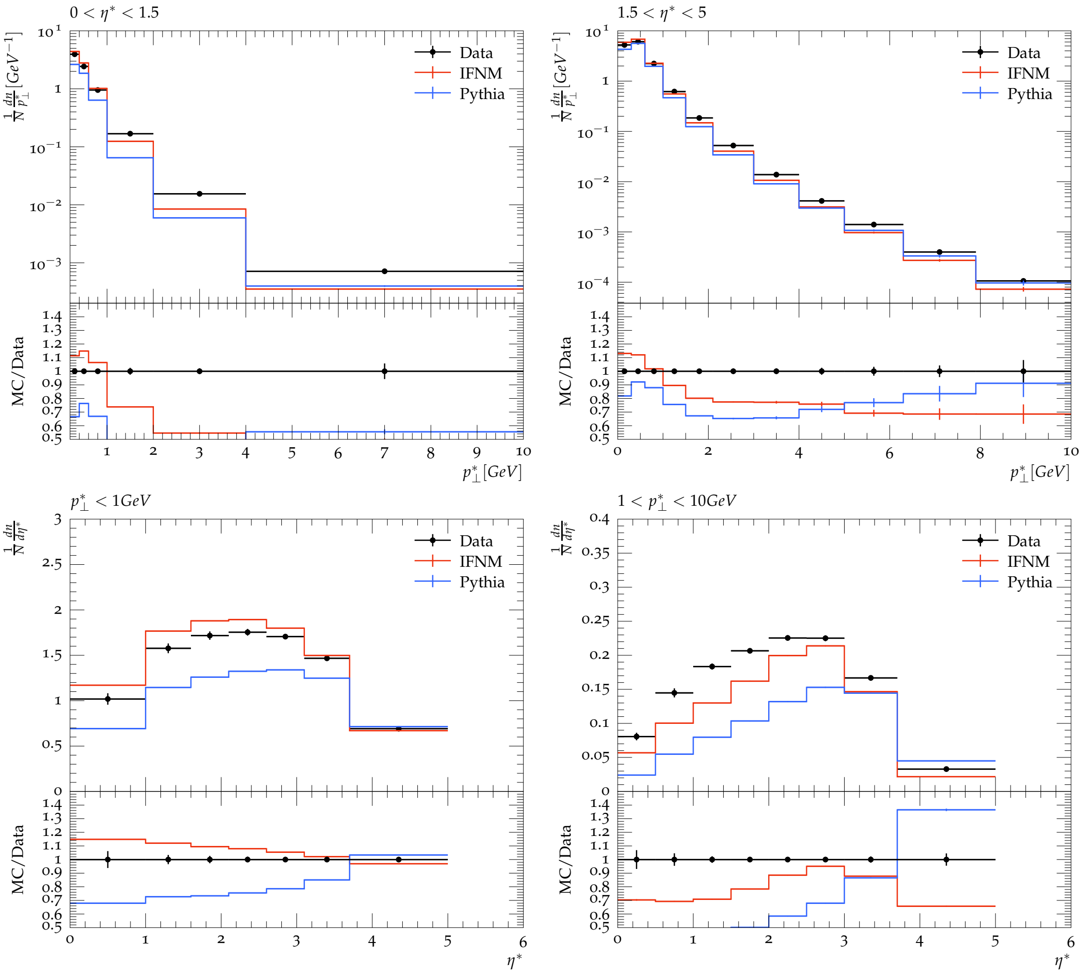

Figure 8: The Charge particle spectra compared to HERA data

We can see that there is a difference between Pythia and Rapgap, because in Pythia we only can calculate the leading order of the scattering processes. On the other hand, in RAPGAP we can calculate the next-to-leading of the matrix elements.

2.2.2 The Validations of The Plots

Here, we focus on the plots of the charged particle transerve momentum spectrum p_T^*

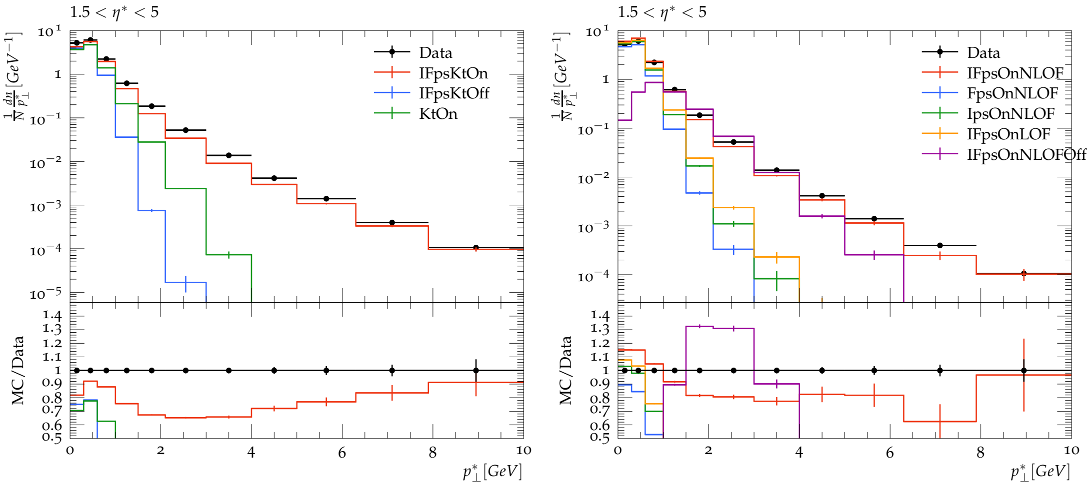

Figure 9: Ln the plot, I : Initial state Parton Shower On, F : final state Parton Shower On, NLO : Next Leading Order correction, F : Hadronization of Fragmentation On, and LO : Leading Order

As we can see in left plot that the intrinsic transverse momentum k_T will fill the charged particle spectrum at very small transverse momentum p_T^*. From the right plot, the initial and final parton shower will fill the charged particle spectrum at higher transverse momentum p_T^*. For both plots, the fragmentation will fill the tail of charge particle spectrum. Moreover, we can also see that the contribution to charged particle spectrum from the initial state parton shower, final state parton shower look very similar. Besides, the intrinsic transverse momentum the initial state parton shower and final state parton shower are ver similar at transverse momentum p_T^* near zero. Then, we want to look at these conditions whether or not they behave differently at larger Q^2. Then, we increase the positron and proton beam's energy.

2.3 At a higher Resolution Scale Q^2

We now look at the charged particle spectrun at $10000 < Q^2 < 20000 GeV^2$. Then, we obtain the charged particle spectrum as shown in Fig 10.

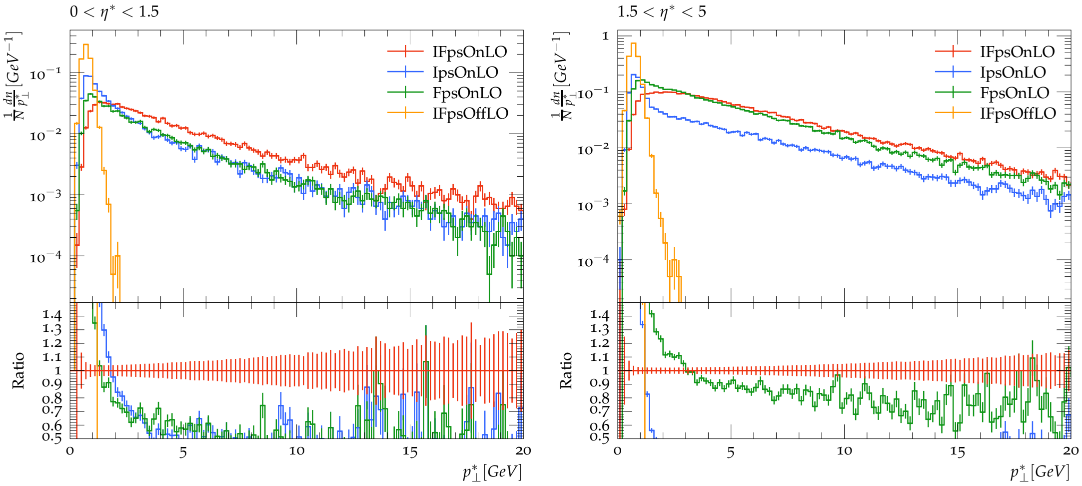

Figure 10: Ln the plot, I : Initial state Parton Shower On, F : final state Parton Shower On, and LO : Leading Order

In the right plot where $1.5 < \eta^* < 5$, we can see the different behaviour of the initial state parton shower and final state parton shower on the charged particle spectrum. As we can see again, the charged particle spectrum is influenced by the intrinsic transverse momrntum k_T at small transverse momentum p_T^*, and parton shower at higher transverse momentum p_T^*. However, this $1.5 < \eta^* < 5$ the parton shower from final state will have higher impact than initial state on the charged particle spectrum. This shows us that in such a region, the hard scattering processes occur. However, when we look at $0 < \eta^* < 1.5$, the effect of parton shower of initial and final is very similar or almost the same. As a result, we want to know what would happen if we calculate the charged particle spectrum at the negative $-5.0 < \eta^* < -1.5$ region which is the region that cannot be observed at HERA. Then, for the negative η^* region, the result as shown in Fig 11.

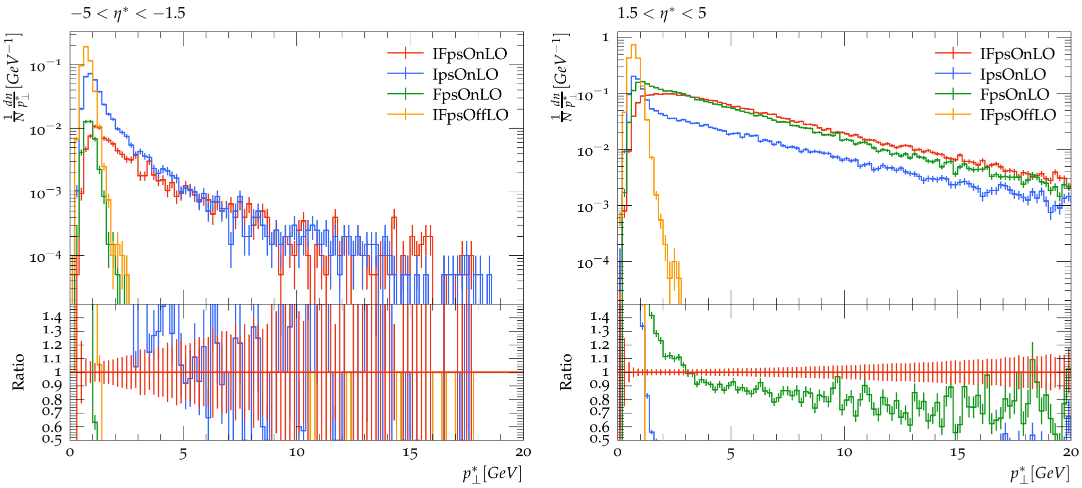

Figure 11: Ln the plot, I : Initial state Parton Shower On, F : final state Parton Shower On, and LO : Leading Order

Here in $-5 < \eta^* < -1.5$ region, we can see the effect of parton shower on the charged particle spectrum are different from the plot in $1.5 < \eta^* < 5.0$ region. The plot in $-5 < \eta^* < -1.5$ region shows that at small p_T^*, the charged particles spectrum is still dominated by intrinsic k_T,and at high p_T^* in negative η^* the initial state parton shower will play an important role larger than the final state parton shower.

3 Conclusion

3.1 Summary

As we see that in order to have a good the explanation of charged particle spectra, one needs to take the intrinsic transerve momentum k_T, the parton shower, and fragmentation phenomena into an accout. We then see a good agreement between the Monte Carlo simulation and the data from HERA. Moreover, we can also distinguish the effect of the intrinsic k_T and the parton shower at different values of p_T^*. In all cases of η^*, at small values of p_T^* the intrinsic k_T would play an important role and have less impact on the charged particle spectrum at higher values of p_T^* . In the case in which $\eta^* > 0$ the final state parton shower would take place and start dominating the initial state parton shower. On the other hand, in negative η^* region, the initial state parton shower would dominate the final state parton shower. Therefore, we would also expect that this behaviour of the charged particles spectrum at large Q^2 can be studied at LHeC where we can have a high energy beams of particles so that we can access such a region of negative η^*.

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