Charged and leading-charged particle spectra in different final states at $\sqrt{s} = 13$ TeV

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Abstract

To have a better understanding on the transition from the perturbative to the non-perturbative region, we studied the effects of different phenomenological parameters included in modern Monte Carlo event generators, and also the importance of Multi Parton Interactions (MPI). All these studies were done for charged particle spectra in an event selection where we included an inclusive sample, and Single Diffractive (SD) and Non-Single Diffractive (NSD) dissociation enhanced samples, at $\sqrt{s} = 13$ TeV. The predictions were done using Monte Carlo generator, PYTHIA 8 with the tune CUETP8s1. The different studies are compared with experimental data.

Contents

1 Introduction

Scattering processes at high energy hadron colliders are traditionally classified as either soft or hard. The underlying theory for all such processes is the Quantum Chromodynamics (QCD), but the approach is very different for the two cases.

The hard sector involves large momentum transfers (high p_T or high mass at the final state), processes with sufficient high energy scale where quarks and gluons can be considered as free particles and the rates and event properties can be predicted with some precision using perturbative QCD (pQCD).

Soft processes dominates the hadronic scattering cross-sections and are characterised by an energy scale of the order of the hadron size (1 fm $\approx$ 200 MeV) [1] and low momentum transfers. In this region the coupling constant (α_s), determining the strength of the interaction, is large enough to make the higher order terms non-negligible and the perturbative expansion in power of α_s is no longer possible, making the process intrinsically non-perturbative, which effects are much less understood.

Most of the final-state hadrons produced in pp collisions arise from hadronisation of quarks and gluons scattered through "semi-hard" interactions. In QCD, the theoretical parton-parton cross section $d\sigma_{2\to 2}/dp_T^2 \propto \alpha_s^2(p_T^2)/p_T^4$, where α_s is the strong coupling, has a divergence as p_T goes to 0 and the integrated cross section, given by the next equation

$$\sigma(p_T^{min}) = \int_{p_T^{min}} (d\sigma/dp_T^2) dp_T^2 \tag{1}$$

exceeds the total inelastic cross section, this occurs at p_T^{min} values of the order of 4-5 GeV.

Model calculations of hadronic collisions, like is the case of PYTHIA 8, regulates such problem introducing an effective parameter $p_{T,0}$ connected to the confinement scale of hadrons. And then we have:

$$\frac{d\sigma_{2\to 2}}{dp_T^2} \propto \frac{\alpha_s^2(p_T^2)}{p_T^4} \to \frac{\alpha_s^2(p_T^2 + p_{T,0}^2)}{(p_T^2 + p_{T,0}^2)^2} \tag{2}$$

But, after fixing this divergent behaviour the partonic cross section still bigger than the σ_{inel}. This excess is interpreted as the presence of MPI in such a way that $\sigma_{2\to 2}$ does not exceeds the σ_{inel}.

To describe soft processes the theory adopted is the Regge theory which says that the soft hadronic phenomena at high energies are universally dominated by the exchange of the Pomeron ($\mathbb{P}$), which is described as a colourless and flavourless multiple gluon [2] or a glueball exchange.

1.1 Proton-proton (pp) collisions

In hadron-hadron collisions, interactions can be either elastic or inelastic depending on the characteristics of the final states.

Elastic interactions: the initial and final state particles are identical, both protons emerge intact and no other particles are produced ($p_1 + p_2 \rightarrow p'_1 + p'_2$, see Figure 1(a)). The LHC cross-section (at $\sqrt{s} = 14TeV$) for elastic scattering is ∼30 mb [3].

Inelastic collisions: As colliding hadrons approach each other, they can interact by a color exchange (Non-Diffractive) or without color exchange (Diffractive). In this kind of collisions, the final state does not need to be identical to the initial state, and more particles are produced.

There are several descriptions of diffraction. We focus in the one described by Regge theory [4]. This states that a diffractive reaction is one in which no internal quantum numbers are exchanged between the colliding particles. Diffraction occurs when one or two Pomerons are exchanged, and none, one or both protons dissociate into multi-particle final state with the same quantum numbers of the colliding protons, this system of particles is referred to as the diffractive system. Diffraction can be either soft or hard and the transitions between the two descriptions is not well understood.

The diffractive dissociations can be:

Single Diffractive (SD): Occurs when only one of the protons dissociates ($p_1 + p_2 \rightarrow p'_1 + X_2$ or $p_1 + p_2 \rightarrow X_1 + p'_2$, see Figure 1(b)). The LHC cross-section (at $\sqrt{s} = 14TeV$) for SD is ≈ 10 mb [3].

Double Diffractive (DD): When both colliding protons dissociate ($p_1 + p_2 \rightarrow X_1 + X_2$, see Figure 1(c)). The LHC cross-section (at $\sqrt{s} = 14TeV$) for DD is ≈ 7 mb [3].

Central Diffractive (CD) or Double Pomeron Exchange: Is carry out when two Pomerons are exchanged ($p_1 + p_2 \rightarrow p'_1 + X + p'_2$, see Figure 1(d)). In this process, both protons interact and are seen in the final state. The LHC cross-section for CD is ≈ 1 mb [3].

Non-Diffractive (ND): In this case, there is an exchange of colour charge and subsequently more hadrons are produced (see Figure 1(e)). These interactions are the dominant process in pp interactions and are expected to be ≈ 60% of all interactions at the LHC with a cross-section of ≈ 65 mb (at $\sqrt{s} = 14TeV$) [3].

The total pp cross-section is given by the sum of the above contributions (equation 3).

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} = \sigma_{el} + \sigma_{diff} + \sigma_{ND} = \sigma_{el} + \sigma_{SD} + \sigma_{DD} + \sigma_{CD} + \sigma_{ND} \qquad (3)$$

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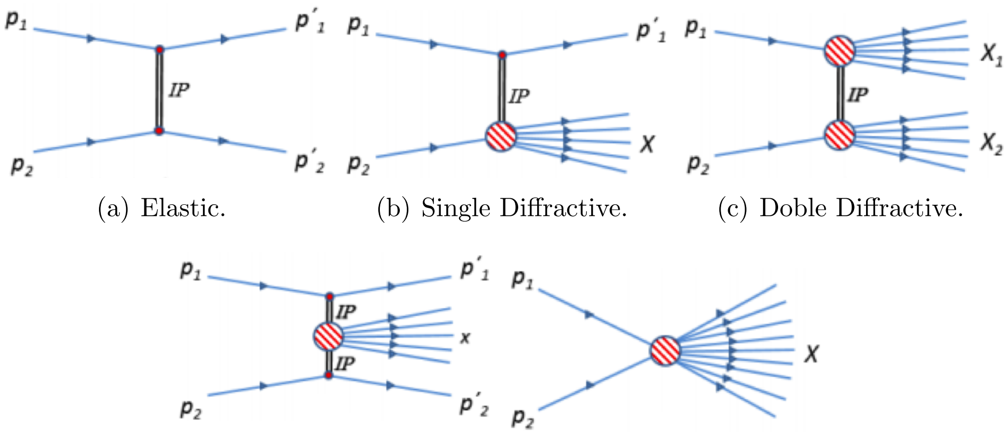

(a) Elastic. (b) Single Diffractive. (c) Doble Diffractive.

(d) Central Diffractive. (e) Non-Diffractive.

Figure 1: Diagrams of different proton-proton interactions

2 Observables and Event Selection

2.1 Observables

The measured observables in this work are:

- **Pseudorapidity** (η): a spatial coordinate describing the angle of a particle relative to the beam axis. It is defined as:

$$\eta \equiv -\ln[\tan(\frac{\theta}{2})] \tag{4}$$

where θ is the angle between the scattered particle and the beam pipe.

- **Transverse Momentum** (p_T): if we choose the z-axis like the direction of the beam, the transverse momentum is

$$p_T = \sqrt{p_z^2 + p_y^2} \tag{5}$$

- **Cross section**: is the probability that two colliding particles will exhibit a specific reaction. It is expressed in terms of units of area.

2.2 Event Selection

For this analysis, we selected the events in such a way to create event enhanced samples in SD, NSD and a Inclusive sample, where NSD includes DD, CD and ND dissociations. The inclusive sample was select with at least one charged particle in a pseudorapitidity region restricted by $|\eta| < 2.4$, which corresponds to the Tracker acceptance of the CMS detector. In addition to this, events with at least one particle with energy $E_{part} > 5$ GeV in the ranges $3 < |\eta| < 5$, also known as forward regions are selected. These forward regions corresponds to the acceptance of the Hadronic Forward (HF) calorimeters of CMS experiment. For that conditions we select the NSD and SD enhanced event samples with the next conditions:

NSD enhanced: At least one particle with $E_{part} > 5$ GeV in both forward regions. This can be seen in the detector as:

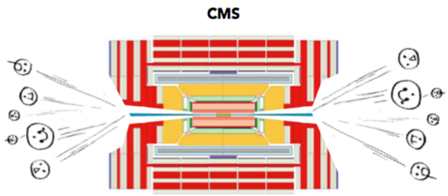

Figure 2: NSD dissociation events in the detector.

and,
SD enhanced: At least one particle with $E_{part} > 5$ GeV in just one forward region.

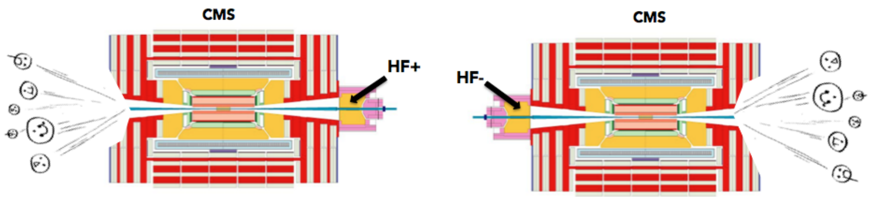

Figure 3: SD dissociation events in the detector.

We obtained SD+ and SD- enhanced samples depending on the η values, or in which HF we had the events, in this work, we only show SD+ since the other is symmetric and does not provide additional information.

The motivation for studying diffractive scattering is that it offers an opportunity to explore the interesting transition from “soft” to “hard” physics in different kind of interactions, where we can also study the effects of Multi Parton Interactions (MPI).

Measured the charged particle spectra for the different final state enhanced samples for charged particle with $p_T > 0.5$ GeV in $|\eta| < 2.4$ with a centre-of-mass energy $\sqrt{s} = 13$ TeV, which is the energy at which the LHC is currently running. For this, the RIVET (Robust Independet Validation of Experiment and Theory) package was used with predictions of the Monte Carlo (MC) generator, PYTHIA 8 [5] with the tune CUETP8s1. The different studies are compared with experimental data.

3 Results

3.1 Regularization scale $p_{T,0}$

3.1.1 $p_{T,leading}$ distributions

The effects of varying the $p_{T,0}$ parameter are studied in the pseudorapidity and integrated $p_{T,leading}$ distributions. The Figure (4) shows the cross sections as a function of the minimum transverse momentum of the leading particle

$$\sigma(p_T^{min}) = \frac{1}{N_{evt}} \int_{p_T^{min}} (dN/dp_T^{lead}) dp_T^{lead} \tag{6}$$

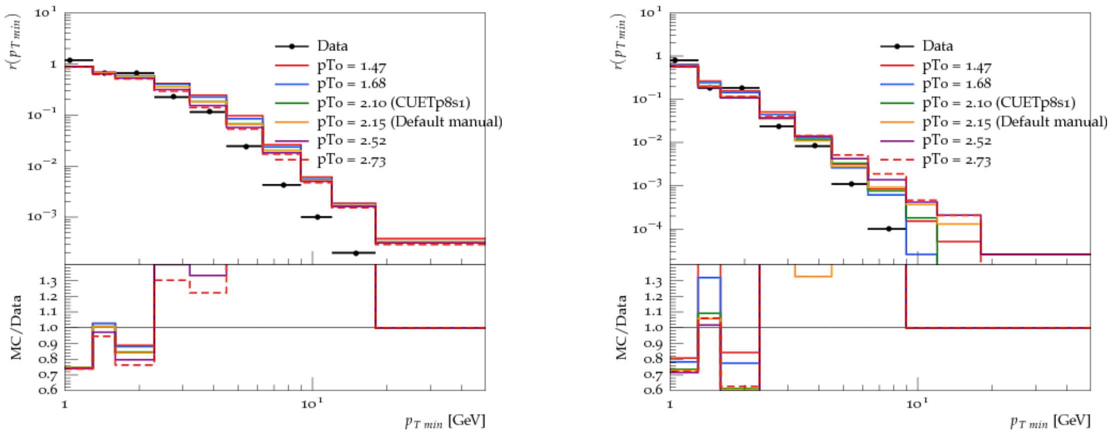

Figure 4: (Left) NSD enhanced: $E_{part} > 5$ GeV in $-5 < \eta < -3$ and in $3 < \eta < 5$; (Right) SD+ enhanced: $E_{part} > 5$ GeV in $3 < \eta < 5$ and NOT in $-5 < \eta < -3$, both cases compared to data

In the left plot of Figure (4), we can see a "pattern" for $p_{T,0}$ values in the case of the NSD enhanced sample, this tell us that for larger values of $p_{T,0}$ the saturation is reached first than for lower values. For the SD enhanced sample this pattern can not be seen because SD dissociation is below of the $p_{T,0}$ scale, then we can say that this distribution is insensitive to this regulator parameter.

3.1.2 Pseudorapidity distributions

In the case of the pseudorapidity distributions we obtained the next results:

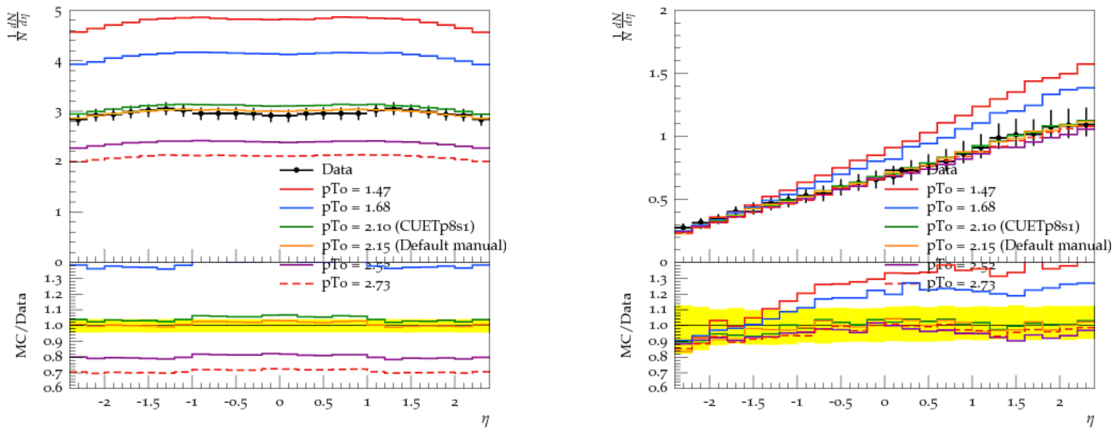

Figure 5: Sensitivity to the $p_{T,0}$ regularization parameter. (Left) Selection: inclusive selection; (Right) SD+ enhaced: $\mathrm{E}_{part} > 5$ GeV in $-5 < \eta < -3$ & NOT in $3 < \eta < 5$.

In the left plot of Figure 5 we can see that in the case of the inclusive event selection, the shape of the distribution does not chance under variations of $p_{T,0}$, and also that for small $p_{T,0}$ we are going to have a higher amount of particles, and for lower values, less particles are produced. For the SD+ enhanced (right plot of Figure 5) we see that there is no so much difference in the side of the scattered proton, but for low $p_{T,0}$ values there is an increase of particles in the side of the diffractive system ($\eta > 0$).

3.2 Soft and hard contributions for diffractive processes

In PYTHIA 8, the soft and hard contributions can be parametrized with introducing the parameter *Diffraction:mMinPert* $= X$ [6], this parameter fix the minimum mass of the diffractive system produced perturbatively. Setting this value $X >$ centre-of-mass (CM) energy will suppress the perturbative description. In order to have a better idea of the transition between soft and hard contributions, we analysed several values of *mMin-Pert*, the results can be seen in Figure (6) where a comparison to the pseudorapidity distribution of SD enhanced sample is shown.

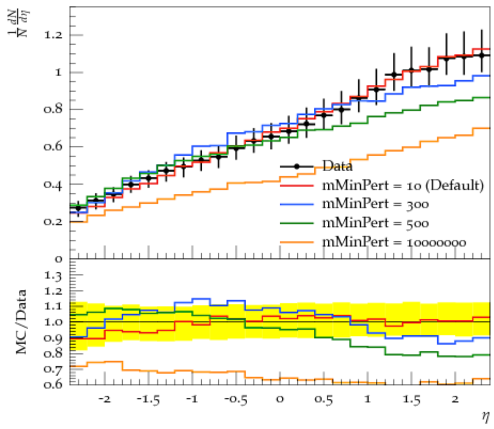

Figure 6: SD+ enhanced: $E_{part} > 5GeV$ in $3 < \eta < 5$ and NOT in $-5 < \eta < -3$.

As we can see, less particles are produced when we have only soft processes. From this plot we can also see that a small amount of particles of the diffractive system could reach the tracker side of the proton who does not suffer the dissociation (left side of the plot), these particles seems not to be that sensitive by the hard description.

3.3 Multi Parton Interactions (MPI)

Protons are composed of three valence quarks and many gluons that bind the quarks, when protons interacts several parton-parton interactions can occur, to have a better illustration we can see a diagram in Figure (7).

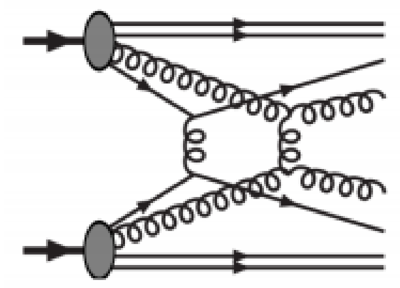

Figure 7: Sketch of Multi Parton Interactions.

In PYTHIA 8, is possible to turn on or off the MPI contributions. In order to see the effects of this phenomena, were produced (see Figure 8) are shown predictions for these two cases.

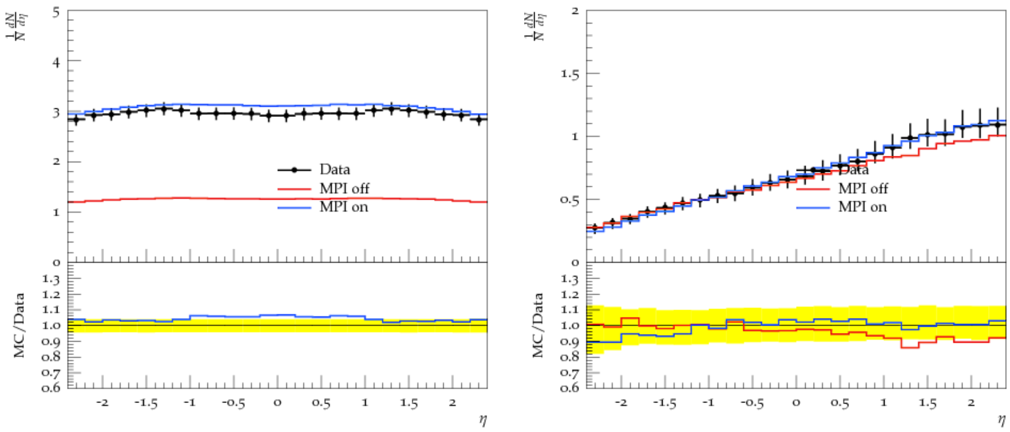

Figure 8: MPI predictions are compared with the data. (Left): Selection: inclusive pp; (Right): SD+ enhaced: $E_{part} > 5$ GeV in $-5 < \eta < -3$ & NOT in $3 < \eta < 5$.

For the inclusive event selection (Left plot of Figure 8), the prediction of MPI off give ~ 3 times less particles per bin, which is telling us that MPI is important to have a correct description of the data. In the case of the SD enhanced (Right plot of the Figure 8), we can see that in the opposite side of the dissociated system (left side of the plot) MPI does not have a strong contribution, and then we can say that the Multi Parton Interaction occurs only in the Pomeron-proton system.

4 Summary

Studies in charged particle spectra for different final state enhanced samples were performed. In particular, we studied the effects of the regulator parameter $p_{T,0}$, the contributions of soft and hard scattering and the importance of multi partonic interactions.

We saw that $p_{T,0}$ variations in the case of the inclusive event selection have a big effect in the integrated $p_{T,leading}$ distribution, and not so big effects on the case of the SD enhanced sample. Also the amount of particles produced is affected for the inclusive selection, but only in the side of the diffractive system in the case of the SD enhanced sample.

We can also conclude, that the balance between the soft and hard descriptions is important to produce the right amount of particles.

Finally, we showed that MPI is essential to describe the pseudorapidity distributions, and we learned that PYTHIA 8 includes MPI for SD only in the Pomeron-proton system.

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