Investigation of inclusive and exclusive jets production at the LHC. Comparison between CASCADE and PYTHIA.

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Abstract: The main idea of this project is to make the investigation about the theoretical predictions that describes the ratio of inclusive and exclusive jet production in order to explain the divergences that result from simulations with two Monte Carlo (MC generators of high energy proton proton collisions. These MC generators are PYTHIA and CASCADE. As a result of this project we have that, due to the fact that in CASCADE one possible type of interaction is considered, $gg \to q\bar{q}$, then in this MC generator the ratio tends to increase with respect larger values of rapidity separation of the jets.

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1 Introduction

In high energy collisions may be produced collimated sprays of multiples particles, called "jets". This jets must be measured in a particle detector and studied in order to determine the properties of the original quark and give us important information about underlying partonic processes.

A jet, specifically, is defined as a collimated bunch of hadrons (or decays products of hadrons) produced by hadronisation of partons roughly in the same direction .

To identify hadrons as jets, jets algorithms are used, which map the momenta of the final state particles into momenta of a certain number of jets. In this report ANTIKT algorithm is used with a parameter resolution equal to 5 ($R = 5$).

In this report, specifically, are considered protons as incoming particles, with a center of masss energy of $\sqrt{s} = 7TeV$, and jets are considered with values of the rapidity within the interval $|y| < 4.7$. In the collisions dijet or higher order of multijets can be produced. Events with at least one pair of jets are denoted as inclusive, and events with exactly one pair of jets are called exclusive.

There are many Monte Carlo (MC) generators in order to simulate collisions process. PYTHIA and CASCADE are two examples of MC generators. The basic difference between them is that the Monte Carlo generators CASCADE are motivated by the leading-logarithmic BFKL approach and secondly, for the simulation of the non-perturbative fragmentation, PYTHIA uses the Lund string model as model hadronisation. There are others differences between them, such as that in CASCADE only the interaction $gg \to q\bar{q}$ is considered , while in PYTHIA six possibles ways of interactions are included, and also, in CASCADE Multi Parton Interactions (MPI) are not simulated.

In this project the mean idea is to make the comparison between MC generators as CASCADE and PYTHIA in order to see and explain the divergence between them in jet productions events. Simulations are performed with

PYTHIA, in order to study MPI and the Hard QCD processes independently. And secondly a comparison between PYTHIA and CASCADE is performed.

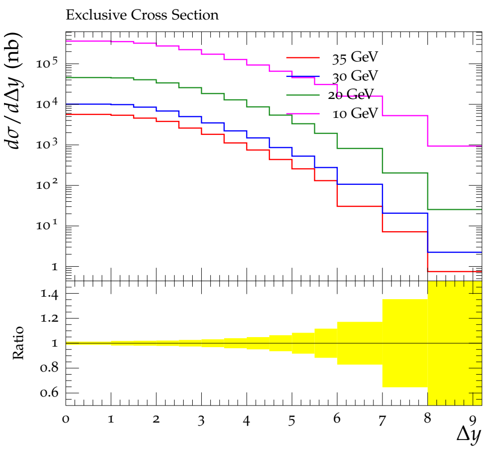
2 Analysis of Jets production with PYTHIA8.

2.1 Cross Section dependence with the minimum transversal momentum in Hard QCD process.

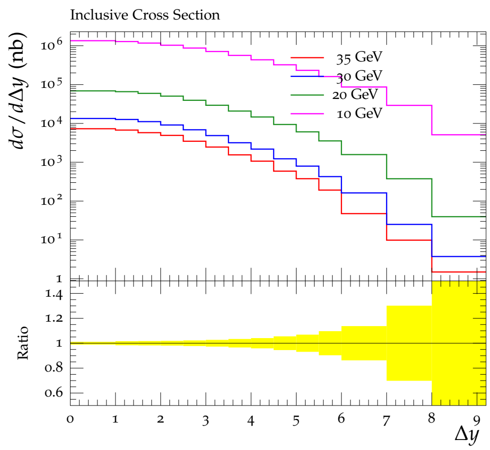
Perturbative QCD is a field of particle physics in which the theory of strong interactions, Quantum Chromodynamics (QCD), is studied by using the fact that the strong coupling constant (α_s) is small at high energies or short distance interactions, thus allowing perturbation theory to be applied. Jet creation, is considered as a hard QCD process which can be studied by perburbative methods (pQCD). The probability of creating a certain set of jets is described by the jet production cross section, which is an average of elementary perturbative QCD quark, antiquark, and gluon processes, weighted by the parton distribution functions.

It is necessary to determine the minimum threshold of the value for the transversal momentum, $p_{\perp_{min}}$, because low values affect the perturbative cross section and hence the comparison between theory predictions and experimental data.

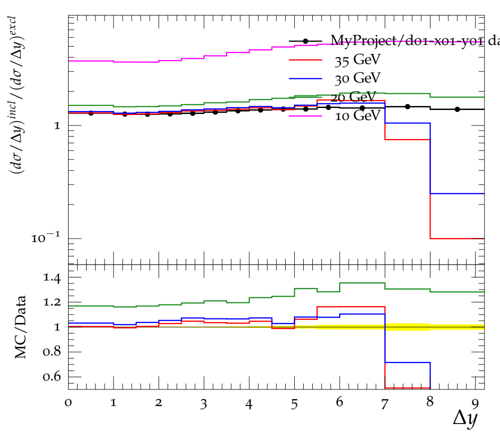
Here is made a comparison, taking into account different values of $p_{\perp_{min}}$, to check how it changes the inclusive and exclusive jet cross section and the ratio between them. The differential cross section is plotted with respect to the separation of the rapidity for each possible combinations of jets in the exclusive and inclusive cases, where in the inclusive case, the rapidity separation is evaluated for each pairwise combination of jets. In order to illustrate better the influence of this, the ratio between inclusive and exclusive cross sections is plotted for different values of $p_{\perp_{min}}$. Are also provided the experimental values of the ratio between inclusive and exclusive cross sections from CMS detector, where measurements were performed under the same condition as were the simulations (taking only jets with larger values of the transversal momentum than 35 GeV). The results are presented in the following figure (Fig.1).



(a) Exclusive events



(b) Inclusive events



(c) Ratio Inclusive-Exclusive Cross Section

Figure 1: Cross Section distribution as a function of the rapidity separation of jets for inclusive and exclusive events.

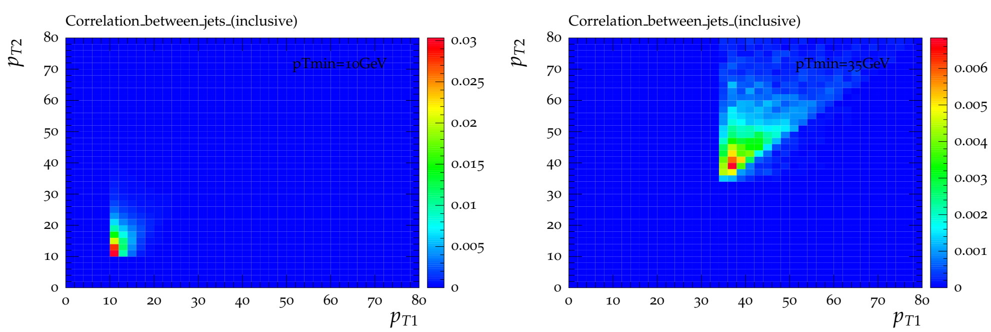
As a generals behavior, for all values of $p_{\perp min}$ we observe that jets separated by larger values of rapidity are less likely, and that the ratio between inclusive and exclusive cross sections are approximately constant with respect to increasing separation rapidity. As those processes governed by BFKL evolution, should lead to an increase of the ratio with increasing the separation between jets, it means that BFKL effects are not visible.

Additionally, it can be noted that inclusive and exclusive cross sections are larger with lower values of $p_{\perp min}$, and the ratio between inclusive and exclusive cross section is larger too, with lower value of $p_{\perp min}$, this means that with lower values of $p_{\perp min}$ the exclusive cross section is lower with respect to the inclusive cross section.

2.2 Correlation between the transversal momentum of the jets.

An interesting point of study is to see the correlation between the transversal momentum of the each pairwise of jets, and how the $p_{\perp min}$ actually influences this correlation. In order to see this, we proof each jets is plotted in a histogram 2D the value of the transversal momentum for each component.

In Fig. 2 is shown this correlation, where we can conclude that the relation between the transversal momentum of the components of each of the jets is close to the line equivalent to the same transversal momentum, and this correlation appears symmetric with respect the line $p_{\perp 1} = p_{\perp 2}$, in both cases of $p_{\perp min}$.



(a) $p_{\perp min} = 10GeV$ (b) $p_{\perp min} = 35GeV$

Figure 2: Correlation between transversal momentum of the components of each of the jets.

Other conclusion is that for lower values of $p_{\perp min}$, for example $p_{\perp min} = 10GeV$, values of transversal momentum far form this minimum value are less likely. This relation is due to the rapid growth of the cross section with less values of $p_{\perp min}$ with respect to the transversal momentum. This dependence of the reach for different $p_{\perp min}$ values is shown in the Fig.3.

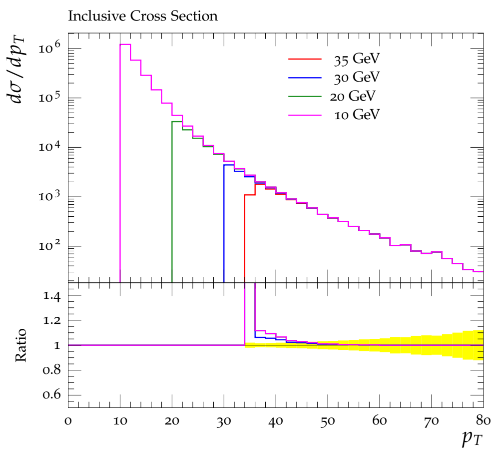
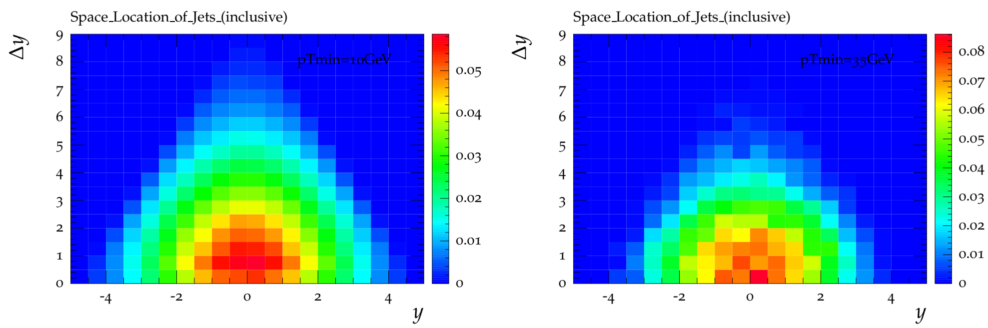


Figure 3: Differential Cross Section distribution with respect the transversal momentum for different value of $p_{\perp min}$.

2.3 Correlation between the average value of rapidity and the Δy between the jets.

We investigate the relation between the average value of rapidity for each pairs of jets($y_{boost} = \frac{y_1+y_2}{2}$) with respect to $\Delta y = |y_1 - y_2|$. In an histogram 2D for inclusive and exclusive events, the relation between y_{boost} and Δy is plotted in order to see the most probable location and separation between all pair of jets. The Fig. 4 shows this correlation for inclusive events for two values of $p_{\perp min}$.

It shows a symmetry around the value $y_{boost} = 0$ (perpendicular direction). Also we can see that for values no close to the perpendicular direction larger values of Δy are less likely, this means that if we have larger values of Δy then is more probable that it was with $y_{boost} = 0$.



(a) $p_{\perp min} = 10GeV$ (b) $p_{\perp min} = 35GeV$

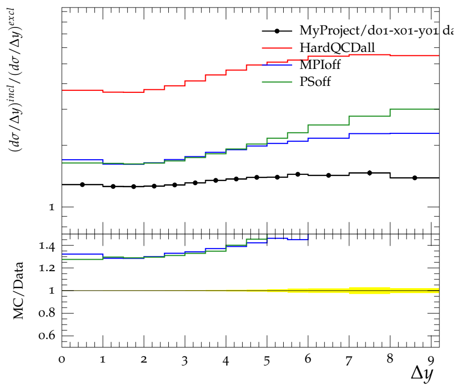
Figure 4: Correlation between the average value of rapidity and the difference of rapidity for each pairwise of components of the jets in inclusive case.

2.4 Influence of the Multi Parton Interactions (MPI) and the Parton Shower (PS).

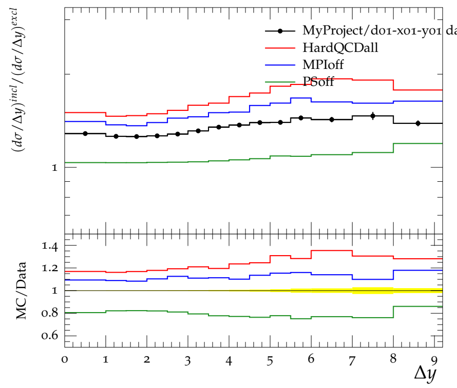
In this section we investigate the influence of Multi Parton Interaction (MPI) and Parton Shower (PS). In the Fig.5 is shown the change of the ratio between inclusive and exclusive cross section when it isn't including MPI and PS for different values of $p_{\perp min}$.

Some important results can be deduced from here, for example, for $p_{\perp min} = 35GeV$ MPI doesn't play a major role and when PS is switch off the ratio between inclusive and exclusive cross section approaches to one, which means that inclusive is closed to exclusive cross section. Events with more than two jets are unlikely, and PS interactions are responsible of trijet and higher order of jets multiplicity.

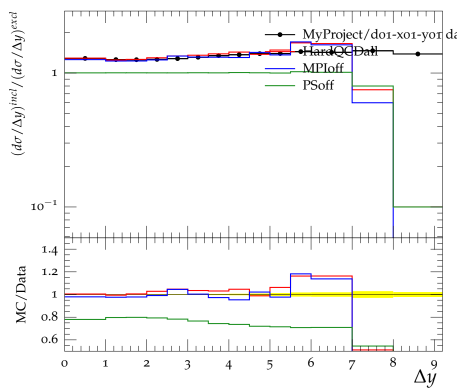
In the Fig.6 is shown the correlation between transversal momentum for



(a) $p_{\perp min}$ = 10GeV



(b) $p_{\perp min}$ =20GeV

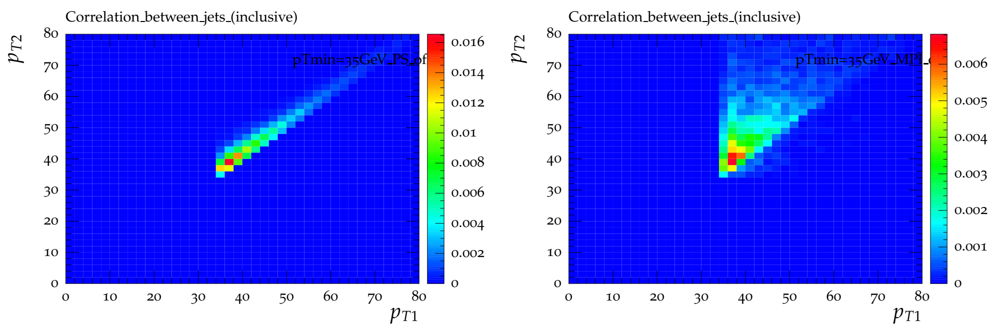


(c) $p_{\perp min}$ =35GeV

Figure 5: Ratio between inclusive and exclusive crosss section in function to the rapidity separation.

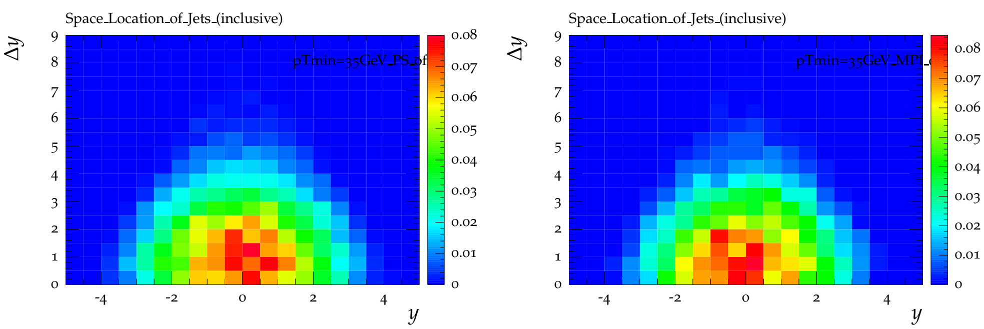
each pair of the jets, and also, in Fig. 7 is shown the correlation of the average value of rapidity and the difference of rapidity for each pairwise of components of the jets. Both cases are when it is taking MPI and PS off and when $p_{\perp mis} = 35GeV$.

The mean results from this is that for PS off, the correlation between the transversal momentum of the components of the jets is more close to the line $p_{\perp 1} = p_{\perp 2}$.



(a) PS off (b) MPI off

Figure 6: Correlation between transversal momentum for each possible pairwise combinations of the components of the jets for PS off and MPI of



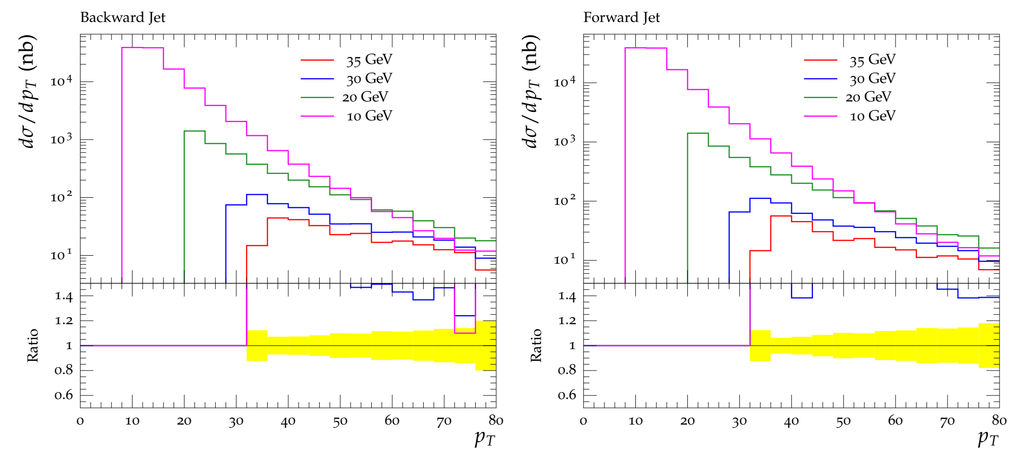
(a) PS off (b) MPI off

Figure 7: Correlation between the average value of rapidity and the diference of rapidity for each parwise of components of the jets for PS off and MPI off.

2.5 Analysis of the case of the trijet production.

In this point are analyzed all events that have exactly three jets. First of all, the jets was sorted by rapidity. The differential cross section as a function of the transversal momentum for each of the jets were obtained, the first jet is considered as the backward jet and the second jet is considered the forward jet. The Fig. 8 illustrate this results for the forward and backward jets, taking into account different values of $p_{\perp min}$.

The third jet is analyzed through the differential cross section with respect ΔR, where ΔR means the spatial separation between the middle component



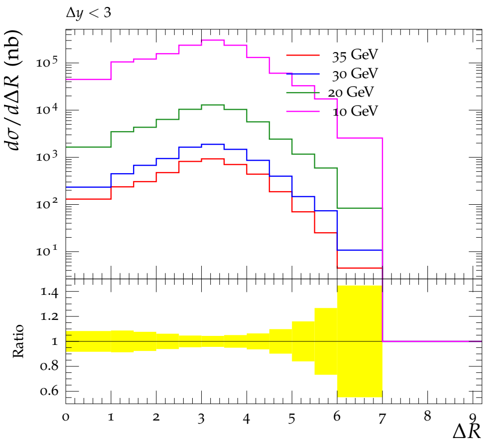
(a) Backward jet (b) Forward jet

Figure 8: Differential Cross section with respect transversal momentum of the backward and forward components of the trijets for different values of $p_{\perp min}$.

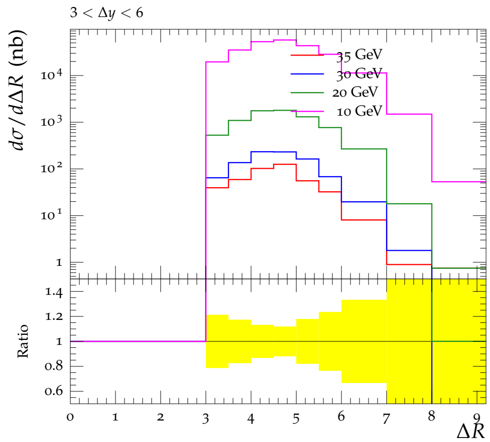
and the forward or the backward components and this spatial separation is taking as:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}, \tag{1}$$

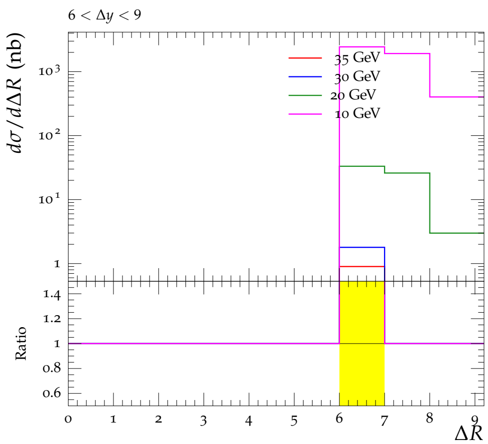
where $\Delta\phi$ is the azimuthal separation of the components of the jets and $\Delta\eta$ is the rapidity separation. The Fig.9 shows this results to different intervals of Δy



(a) $\mid \Delta y \mid < 3$



(b) $3 <\mid \Delta y \mid < 6$



(c) $6 <\mid \Delta y \mid < 9$

Figure 9: Differential Cross section with respect the spatial separation between the middle component of the trijet with respect to the forward and backward components.

2.6 Analysis of the influence of the Hard QCD events.

The jets production is considered in Pythia as Hard QCD process. There are many possibles interactions in Hard QCD process, Fig.10 illustrate these mechanisms.

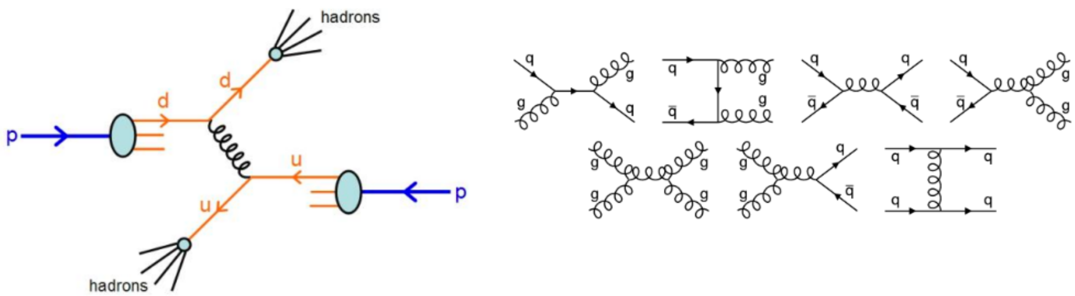
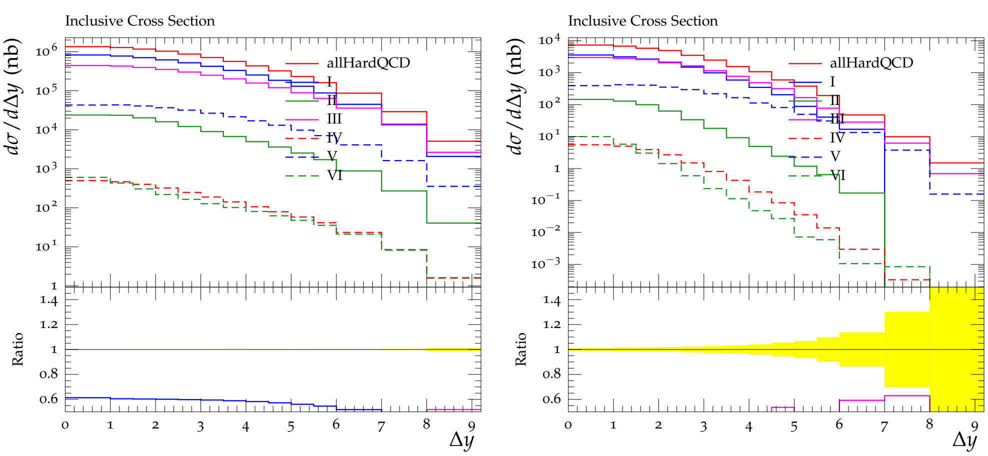


Figure 10: Feynman diagrams for jet production mechanisms. Hard QCD process: $gg \to gg$, $gg \to q\bar{q}$, $qg \to qg$, $q\bar{q} \to gg$, $qq \to qq$. $q\bar{q} \to q\bar{q}$

In order to investigate the influence of each process separately simulations taking into account only one were performed. The Fig11 shows the differential cross sections with respect to the separations of jets by rapidity for two different values of $p_{\perp min}$.

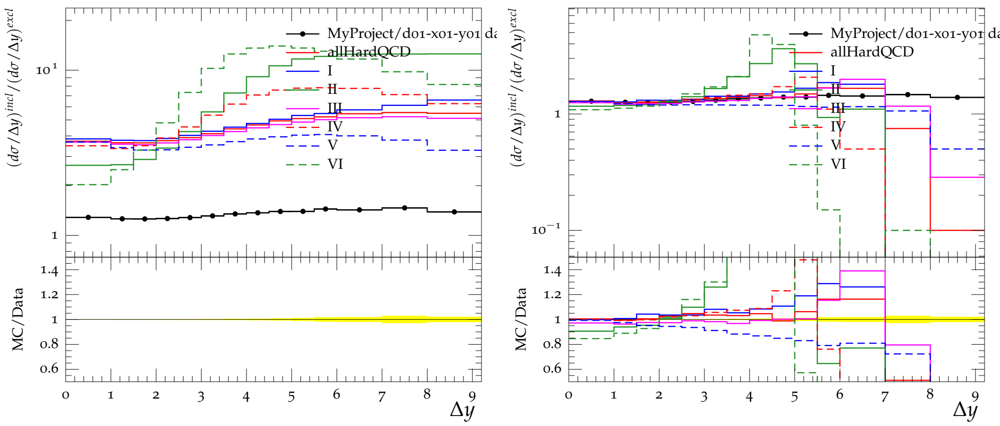


(a) $p_{\perp min} = 10GeV$ (b) $p_{\perp min} = 35GeV$

Figure 11: Differential Cross section with respect rapidity separation taking into account Hard QCD process independently: $gg \to gg(I)$, $gg \to q\bar{q}(II)$, $qg \to qg(III)$, $q\bar{q} \to gg(IV)$, $qq \to qq(V)$. $q\bar{q} \to q\bar{q}(VI)$

It shows us that the Hard QCD processes that take major importance into the cross sections are $gg \to gg$ and $qg \to qg$ while process as $q\bar{q} \to q\bar{q}$ and

$q\bar{q} \to gg$ are less likely. Another analysis was performed seeing the influence of each interaction in the ratio between inclusive and exclusive cross sections shown in the Fig.12.



(a) $p_{\perp min} = 10GeV$ (b) $p_{\perp min} = 35GeV$

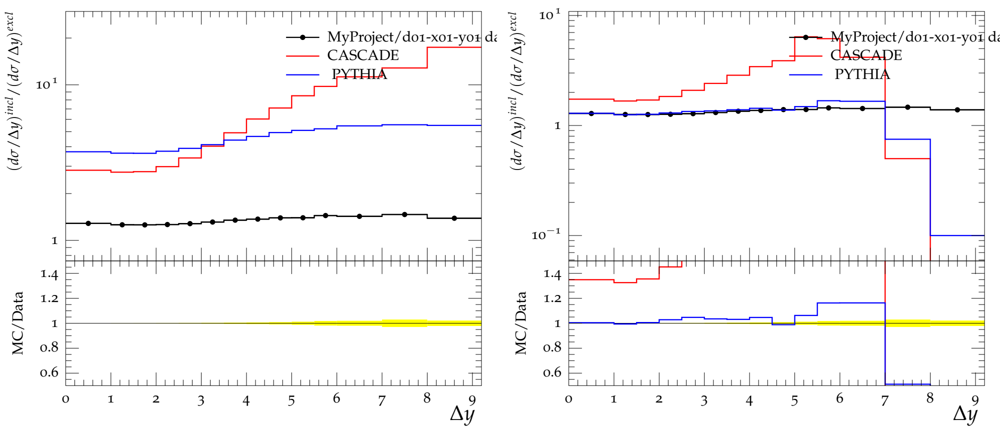
Figure 12: Ratio between inclusive and exclusive cross sections taking into account Hard QCD process independently: $gg \to gg(I)$, $gg \to q\bar{q}(II)$, $qg \to qg(III)$, $q\bar{q} \to gg(IV)$, $qq \to qq(V)$. $q\bar{q} \to q\bar{q}(VI)$

Analyzing the results for $p_{\perp min} = 35GeV$ we can conclude that the process that tend to increase the ratio between inclusive and exclusive cross section with respect to the increase of the separation between jets are $q\bar{q} \to q\bar{q}$ and $gg \to q\bar{q}$, but the probability of the occurrence for these process is much lower than the occurrence probability of $gg \to gg$ and $qg \to qg$. This makes the ratio between inclusive and exclusive cross section in PYTHIA constant with the increase of $\mid \Delta y \mid$. The behavior is similar to $p_{\perp min} = 10GeV$ but now the process more probable tend to increase slightly this ratio.

3 Comparison between CASCADE and PYTHIA simulations.

CASCADE is a MC generator that processes are governed by BFKL evolution equation, this evolution lead to increase of the ratio between inclusive and exclusive cross section, with increasing $|\Delta y|$, and then this behavior is expected. But this may not be the only reason of this behavior. From the above analysis with PYTHIA other conclusions can be made taking into account that in CASCADE only $gg \to q\bar{q}$ precesses are considered and MPI is not taken into account.

The Fig.13 shows the results for the comparison between PYTHIA and CASCADE for two values of $p_{\perp min}$ and the experimental data for $p_{\perp min} = 35GeV$.



(a) $p_{\perp min} = 10GeV$

(b) $p_{\perp min} = 35GeV$

Figure 13: Ratio between inclusive and exclusive cross sections.

The behavior of the CASCADE simulation can be explained because, first of all, can been seen the BFKL effects, and second the process that CASCADE takes into account, $gg \to q\bar{q}$, for Hard QCD interactions, tends to increase the ratio when increase Δy as can been see in the figure 11. This process in PYTHIA is present but it has less probability with respect others process that tends to keep constant this ratio. In the other hand MPI, for this value of $p_{\perp min}$ don't play a major role so this is not one of the reasons for this behavior. Because experimental data are close to the results of PYTHIA simulations.

On the other hand, for lower values of $p_{\perp min}$ as is $p_{\perp min} = 10GeV$, MPI take a significant role, it make that the ratio of the cross sections become bigger, and then, there is a region that the ratio for PYTHIA is bigger than in CASCADE, and on the other hand $gg \rightarrow q\bar{q}$ processes tends to increase the ratio, and then there exist a predominant region where the ratio simulated from CASCADE is bigger than the ratio simulated from PYTHIA.

4 Conclusions

As a general conclusion we have that the ratio of inclusive and exclusive cross section simulated with PYTHIA, for $p_{\perp min} = 35GeV$, it is in agreement with experimental data, and both tend to keep constant the ratio with respect to Δy, while with CASCADE, the ratio tends to increase due to the consideration of $gg \rightarrow q\bar{q}$.

In general for values of $p_{\perp min} > 20GeV$ MPI doesn't play a major role, while the $gg \rightarrow q\bar{q}$ process tends to increase the ratio between inclusive and exclusive cross sections. And finally, for lower values of $p_{\perp min}$, the responsible for the differences between CASCADE and PYTHIA could be the combination between the $gg \rightarrow q\bar{q}$ process and MPI effects.

References

[1] The CMS Collaboration. *Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton proton collisions at $\sqrt{s} = 7TeV$*. 3 April 2012 .

[2] The CMS Collaboration. *Azimuthal angle decorrelations of the jets widely separated in rapidity in proton proton collisions at $\sqrt{s} = 7TeV$.*. 5 May 2013.