Studies of underlying events for $dN/d\eta$ and leading charged particle production

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Abstract

The work described in this report was performed during a summer student project at DESY in Hamburg, Germany. The studies are dedicated to understanding of the underlying events at LHC energies. For that the data collected with the CMS detector at $\sqrt{s} = 8\ TeV$ during a special CMS-TOTEM run are used. The events were triggered by the TOTEM detector, which is located in the presudorapidities range $5.3 < |\eta| < 6.4$. The pseudorapidity distribution as well as the production of leading charged particles are compared to Monte Calo simulations in order to understand the effect of multiparton interactions, sensitivity to certain Monte Carlo parameters and pile up effect. New observables which can be further measured are also presented.

Contents

1 Introduction

One can classify partonic interactions according to the transverse momentum at which the scattering occurs. Interactions with the highest transverse momentum is called hard interaction. Everything except the hard process is referred to the underlying event (UE), Figure 1. Components of the UE are initial and final state radiations, beam-beam remnants and multiparton interactions (MPI). The UE are a very important part to understand the collisions because any hard scatter process is essentially embedded with them.

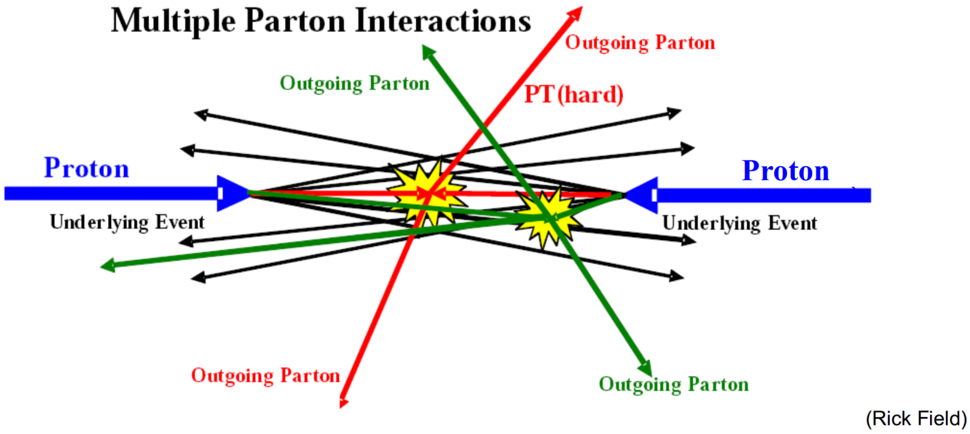

Figure 1: Representation of a pp collision and its parts: hard interaction and UE.

The UE are essentially semi-hard interactions with typical scale of 1-2 GeV and they are amenable to a theoretical description. That is why they need to be modelled phenomenologically. One needs to adjust free parameters of these models in Monte Carlo (MC) generators. This is usually done by comparing the MC predictions with the data of the real experiment (often referred as MC tuning). This is described in more details in section **3.3**.

2 Observables

For this study we chose a group of observables which are perfectly suitable for studies of UE and which can be obtained easily from the experiment and also from the event generators like Pythia[1], in the next lines we explain in an abbreviated way this observables and some interesting effects which are under consideration.

2.1 Pseudorapidity (η) distribution

The pseudorapidity gives us information about the direction of a particle, its definition is

$$\eta = -ln[tan(\theta/2)] \quad (1)$$

as we can see, for $\theta = 90^o$, $\eta = 0$ and for θ values close to zero (π), η goes to ∞ (-∞), in our case this values correspond to the beam pipe. Figure 2 shows the coordinate system of CMS, as seen from the figure θ is defined in the rz plane.

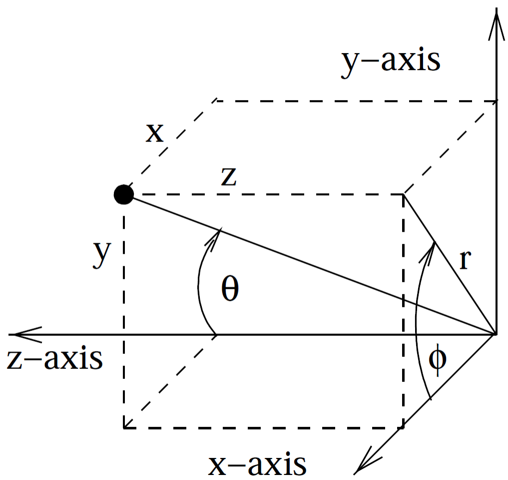

Figure 2: Cartesian, cylindrical and spherical coordinate systems of CMS. All are right-handed. The radius r is the distance to the z-axis, the azimuthal angle ϕ starts from the x-axis in direction of the y-axis, the polar angle θ is the angle relative to the z-axis.

One of the observables which we consider in this report is the density of charged particles per unit of pseudorapidity, i.e. $\frac{1}{N}dn/d\eta$, where N is the total number of selected events. We choose this normalization to obtain the observables which are independent on number of events.

2.2 Leading charged particle distribution

In every collision event there is a particle with the highest transverse momentum, this particle is called leading particle (its transverse momentum is denoted as $P_{t,leading}$). Following the same principle the second highest P_t particle is named as subleading particle ($P_{t,subleading}$).
As in the η distribution, we are interested in the normalized distribution defined as $\frac{1}{N}dn/dP_{t,leading}$, which indicates how many charged particles are produced in average in one event in $dP_{t,leading}$ range. In contrast to the η distribution this is an event observable (one particle per event).

2.3 Multiparton interactions (MPI)

The protons are composed of three valance quarks and many gluons which bind the quarks together, when two protons interact with each other several parton-parton interactions can occurs, for example a quark-quark or gluon-gluon interaction, see Figure 3. As a first approach to understand the collisions we suppose only first hard interaction per collision. Pre-LHC experiments as HERA showed a success of this approach. At LHC energies the comparison of the data with the model based on the single parton scattering shows a large discrepancy. In this energy regime the MPI[2] are important.

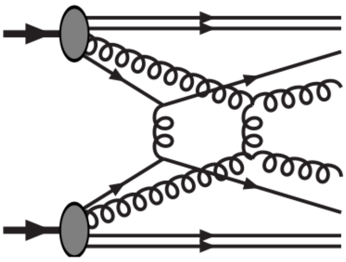

Figure 3: MPI

To show the effect of MPI the measurements of pseudoorapidity and leading charged particle transverse momentum distributions are compared to two Pyhtia predictions: MPI on and MPI off.

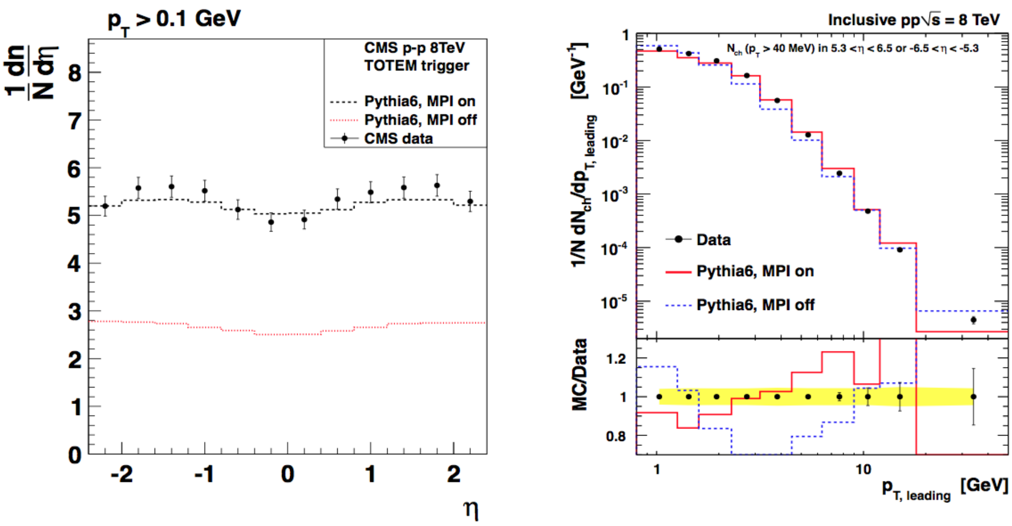

Figure 4: Comparison of the data with Pythia6 MPI on and off. Left $\frac{1}{N}\frac{dn}{d\eta}$ distribution, right $\frac{1}{N}\frac{dn}{dP_{t,leading}}$ distribution.

In Figure 4 (left) the pseudorapidity distribution in the range $(-2.4, 2.4)$ is shown. The data show about 5 particles per η bin and the MC prediction with MPI is in agreement with the data, while without MPI gives roughly speaking two times less particles per bin. In the right plot the $P_{t,leading}$ distribution is shown, the MC predictions with and without MPI are compared with the data. The ratio between data and MC models is shown in the bottom of the figure. Here again we can note a better agreement with the data for the MC with MPI on.
For a better understanding of this increase we introduce a new observable called multiplicity. This quantity tells us about how many charged particles per event are produced. In addition we include a further requirement asking for events where the leading particle has a P_t value greater than 1, 2 or 5 GeV, such distributions are shown in Figure 5.

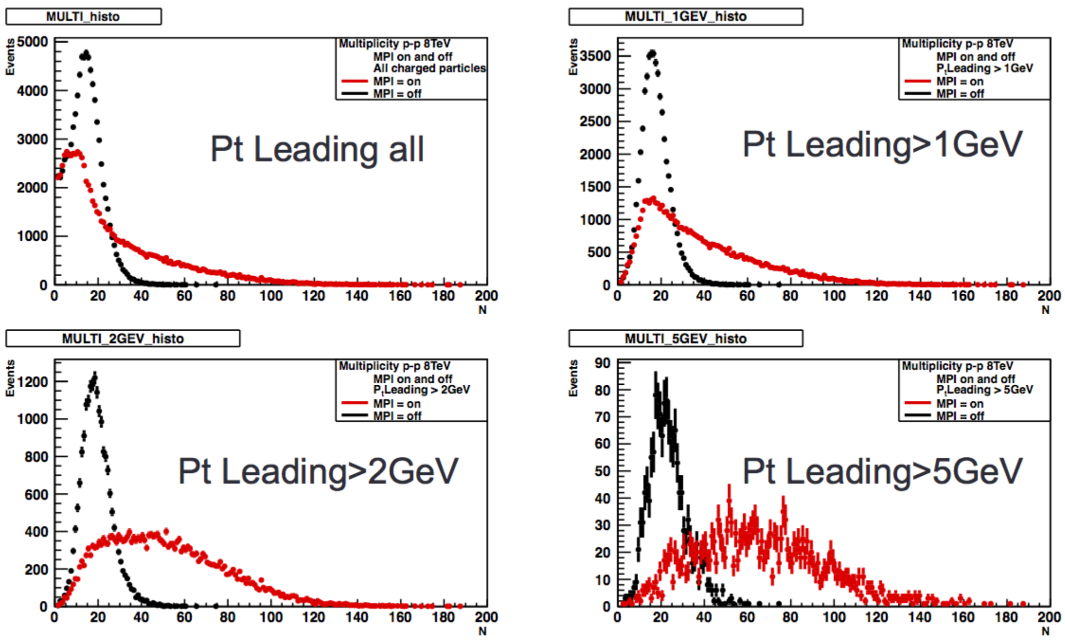

Figure 5: Multiplicity of charged particles for different P_t cuts of leading particle. MPI on (red line) and MPI off (black line)

Here we can see that the shape of the multiplicity distributions without MPI is almost the same for all the $P_{t,leading}$ cuts applied, but with MPI the tail increases telling us that there are more particles produced per event and as we increase the $P_{t,leading}$ cut we find in average more particles in each event (the mean value is shifted to the right).

2.4 P_t balance

In this subsection we are investigating how does the leading charged particle balance in P_t. There are two scenarios for balancing the P_t of the leading particle: i) by the subleading particle or ii) by many soft interactions. As we discus in section **2.2** the subleading particle is the second particle with highest P_t. By soft interactions we mean the initial and final state radiations, which are shown in Figure 6.

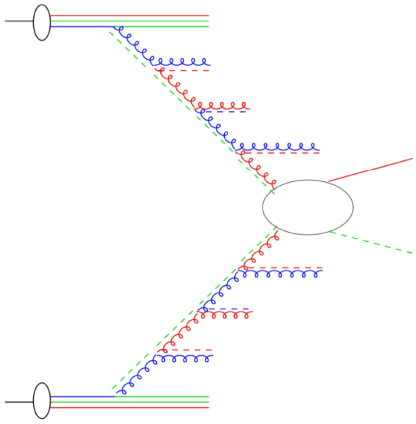

Figure 6: Diagram ilustrainting the initial state radiations (soft processes)

We define the P_t balance as

$$Balance = \frac{P_{t,leading}}{P_{t,subleading}} - 1. \tag{2}$$

If the leading and subleading particles are close to each other in P_t the balance is close to zero. Large values of the Balance indicates that subleading particle does not balance the leading one. The P_t-balance distribution is shown in Figure 7 where the same cuts for the

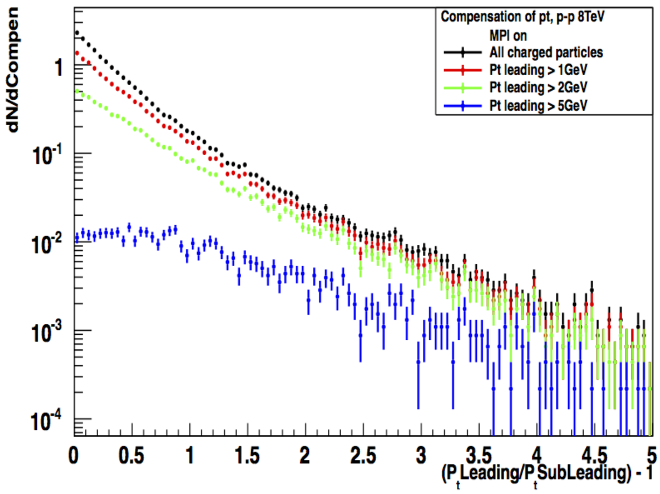

Figure 7: Balance between leading and subleading particles

transverse momentum of the leading particle as in the multiplicity distribution are imposed. One can see that for $P_{t,leading} < 5\ GeV$ there is a very pronounced peak at zero, but for $P_{t,leading} > 5\ GeV$ the shape becomes flatter, telling us the following: for low $P_{t,leading}$ values the leading particle is better compensated by the subleading particle, whereas for high $P_{t,leading}$ it is compensated by many soft interactions.
This suggestion is only in first approximation since we do not know the spatial distribution of the leading particle with the respect to the subleading particle. For further studies we introduce the $\Delta\eta$ and $\Delta\phi$ distributions, which are defined as

$$\Delta\eta = \mid \eta_{leading} - \eta_{subleading} \mid, \Delta\phi = \mid \phi_{leading} - \phi_{subleading} \mid \qquad (3)$$

From Figure 8 one can easily notice that if $\Delta\eta \approx 0$ and $\Delta\phi \approx 0$ the two particles are collinear whereas if $\Delta\eta \approx 0$ and $\Delta\phi \approx \pi$ the particles leave the interaction point in opposite directions (they are back-to-back).

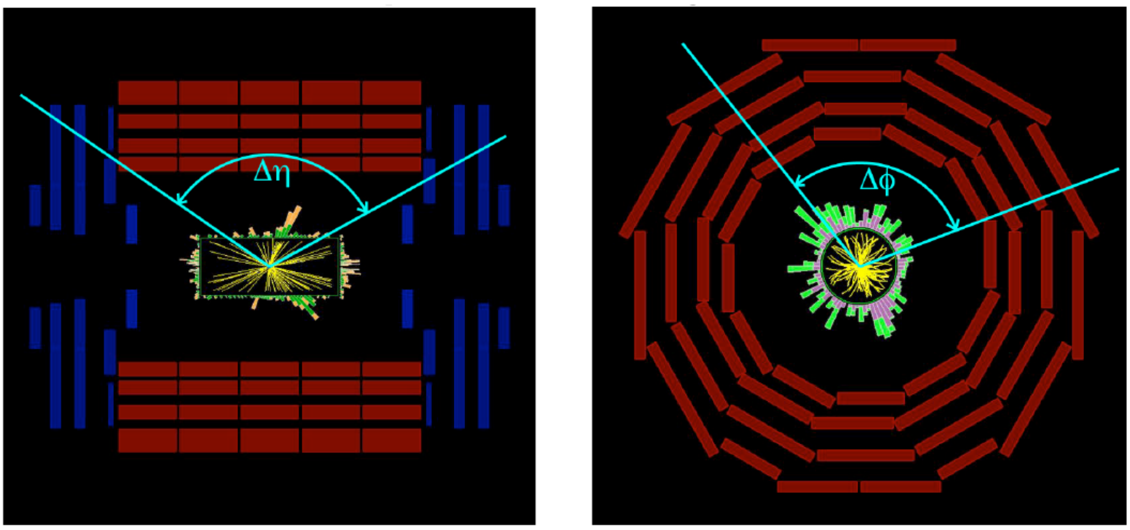

Figure 8: $\Delta\eta$ (Left) and $\Delta\phi$(Right) in the CMS experiment.

Figure 9 shows this spatial distributions. On the left plot we can see that for low $P_{t,leading}$ values the leading and subleading particles are much more close in η than for large $P_{t,leading}$ where the shape is more flat. In the right plot the $\Delta\phi$ distribution is shown where we can note two peaks, one at zero and other at π. As we explained before, the combination of $\Delta\eta \approx 0$ & $\Delta\phi \approx \pi$ means back-to-back behavior, and as we expect from the P_t-balance distribution shown in Figure 7, for $P_{t,leading} > 5\ GeV$ the peak at $\Delta\phi \approx \pi$ is less pronounce, i.e. the compensation is carried out by the soft radiations instead the subleading particle. Also we can note that the collinear behavior for the leading and subleading particles ($\Delta\eta \approx 0$ & $\Delta\phi \approx 0$) keeps the same shape for all the $P_{t,leading}$ cuts.

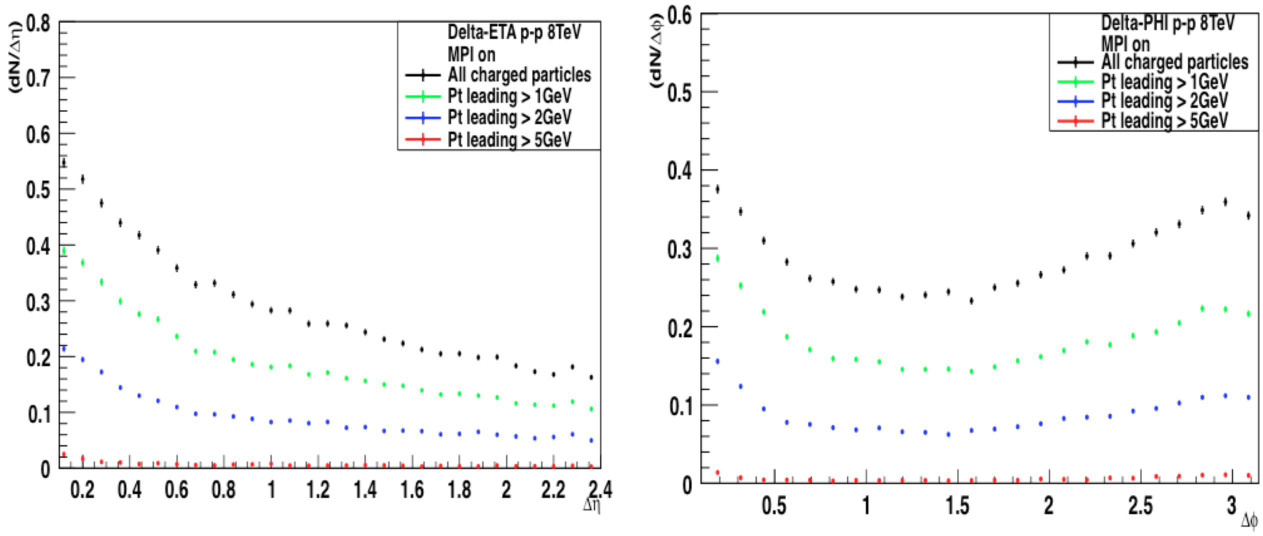

Figure 9: $\Delta\eta$ (Left) and $\Delta\phi$(Right) distributions between leading and subleading charged particles.

3 Monte Carlo studies

The underlying events are not very well understood and one way to improve our knowledge is to use Monte Carlo models.This we do by using our physics knowledge to guess the correct model and values of the free parameters. One way to verify our conjectures is comparing the models with the data of th experiment.

For this work we used as base tune models the default Pythia6, Pyhtia6 Z2*, Pythia8 4C and Pythia8 4Cx where for Pythia8 is included the Minimum Bias Rockefeller model which is discussed in the next section.

3.1 Minimum Bias Rockefeller (MBR)

The MBR[3] is a Monte Carlo simulator embedded in Pyhtia8 addressing the contributions of the three diffraction-dissociation processes to the total-inelastic pp cross section: single-diffraction dissociation (SD), in which only one of the incoming protons dissociates, double-diffraction dissociation (DD), where both protons dissociates, and central-diffraction dissociation (CD), where neither proton dissociates but occurs a double pomeron[1] exchange, Figure 10. The CD process is implemented in Pythia8 for a fist time.
The total cross section (σ_{tot}) is the sum of the total elastic (σ_{el}) and total inelastic (σ_{inel}) cross sections, where the inelastic contribution is calculated as

[1]A family of particles postulated in 1961 to explain the slowly rising cross section of hadronic collisions at high energies.

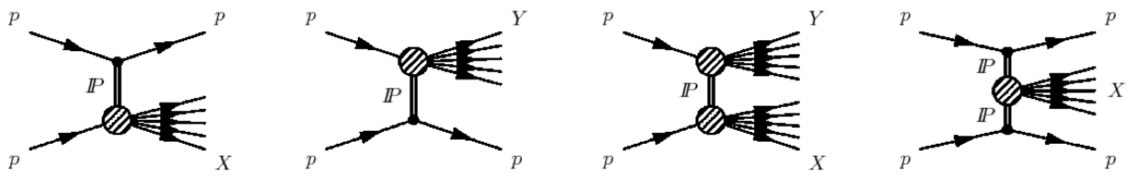

Figure 10: Diagrams of diffractive processes, from left to right; First two are single diffractive (SD),the third corresponds to double diffractive (DD) and the last one is central diffractive (CD).

$$\sigma_{inel} = 2\sigma_{SD} + \sigma_{DD} + \sigma_{CD} + \sigma_{ND}, \tag{4}$$

and ND means non-diffractive process.

In Figure 11 we present the pseudorapidity distribution, the data are compared to Pythia8 with and without MBR option as well with and without CD process to see its final contribution.

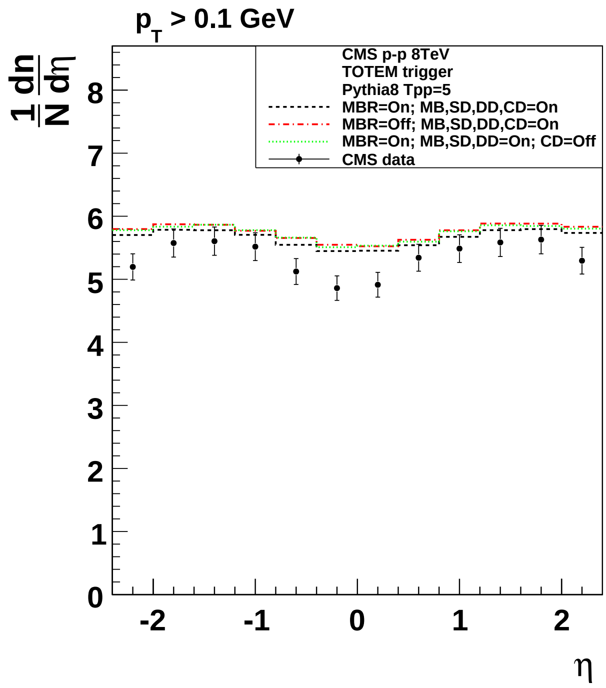

Figure 11: $\frac{1}{N}dn/d\eta$ distribution, tune 4C switching on and off MBR compared with data.

As we can see in the figure the MBR option against the default model for diffractive processes does not show a big effect. Also from here we can conclude that the CD option does not make a difference if we switch it off, but this probably comes from a special event selection we are using. Since we requires at least one charged particle with $P_t > 40$ MeV in the acceptance to the TOTEM detector, the probability to find CD processes is very low (no activity in the TOTEM region).As the result we do not see a big difference by including the CD processes.

3.2 Regularization scale P_{t0}

In hard $2 \to 2$ process interactions the cross sections diverges for small P_t values, that is why in Pythia a regularization parameter called P_{t0} is included. It can be set by the $MultipartonInteractions : pT0Ref = X$, the default value depends on de center of mass (CM) energy. For CM energy of 8 TeV the default value is 2.085 GeV. In Figure 12 we show a strong dependency to this regularizetion parameter, we found in pseudarapidity and $P_{t,leading}$ distributions.

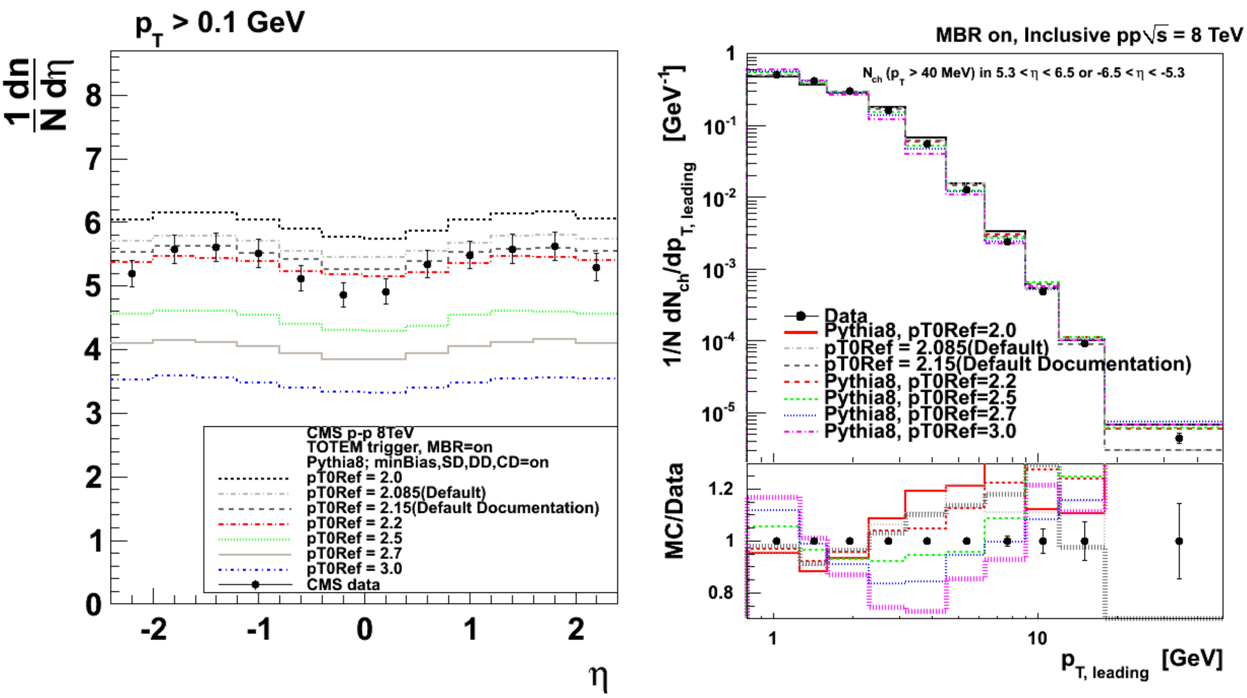

Figure 12: Sensitivity to the P_{t0} regularization parameter. Left: $\frac{1}{N}dn/d\eta$, rigth: $\frac{1}{N}dn/dP_{t,leaging}$

From here we can note that the better value for a more accurate agreement with the data is $P_{t0} = 2.2$ which is very close to the default one. It is important to notice the shape of the pseudarapidity distribution is not changing under variation of P_{t0}, while for leading charged particle distribution the shape changes a lot.

3.3 Monte Carlo Tunes

As mention in the beginning of this section we made the studies with different Pythia tunes to be able to compere the level of agreement reached with them and try to understand the origin of this underlying events. In Figure 13 we present how do the tunes 4C and 4Cx describe the $\frac{1}{N}dn/d\eta$ distribution.

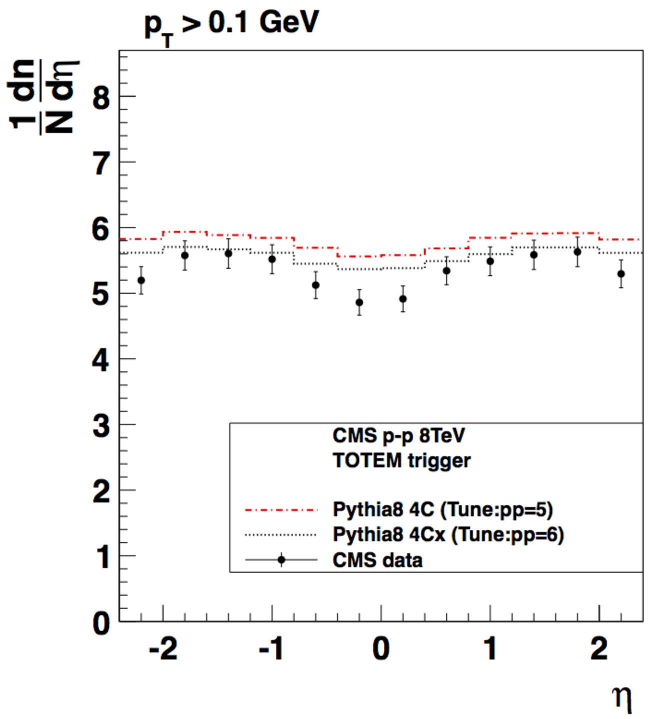

Figure 13: Tune 4C and 4Cx in comparison with data for $\frac{1}{N}dn/d\eta$ distribution

Here we can see that the shape is very similar for two predictions and non of them describes the shape of the data. The normalization is slightly different, tune 4Cx provides better description of the data. This is more or less expected since the 4Cx tune is based on the 4C tune with small changes like the increase of the default P_{t0} regularization factor, this is in agreement with the discussion in the previous section.

4 Pileup studies

In the particle collider experiments to get a certain probability of interaction between beams it is better to collide bunch of particles instead one-to-one particle. In the LHC each bunch contains 1.15×10^{11} protons and when two of these bunches cross each other at CM energies of 7-8 TeV, around 20 collisions occur. This is an important thing to take in count since if more than one pp collision occurs we get more final state particles in the detectors. One first guess is that the amount of final state particles will increase linearly with the number of collisions per event. In Figure 14 we show the pseudorapidity distribution for 1, 2, 3 and 4 pp collisions per event, here is interesting to note the difference between curves is approximately the same (~ 3.5) for all of them except for the bottom one which is at ~ 5 particles per bin.

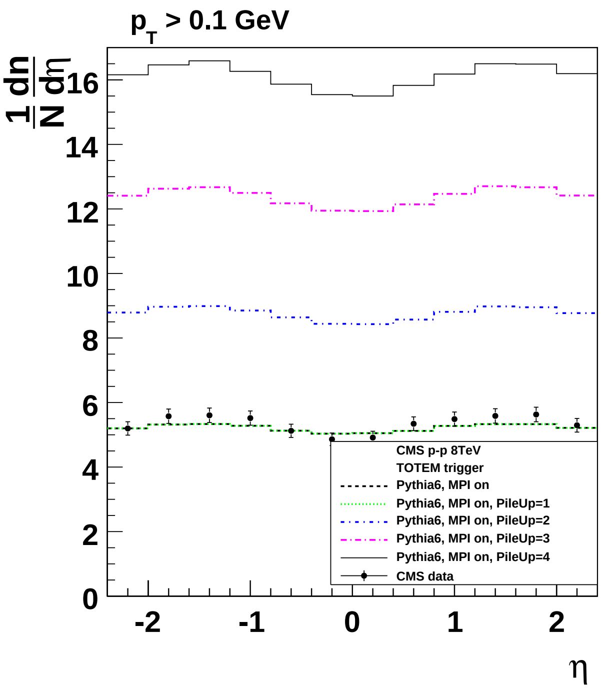

Figure 14: $\frac{1}{N}dn/d\eta$ distribution for different number of pileup events.

Due to special event selection which we required no linear rise of the multiplicity is observed.

5 Summary

The measurement of pseudorapidity and $P_{t,leading}$ distributions provide an useful information to study the underlying events. Now we have a better picture of what is happening with the transverse momentum of the leading particle and the soft processes and its spatial distribution dependance to the CM energy.

Further more the MC studies shows us the following interesting results: i) small effect on MBR implementation, most of all due to the required event selection of at least one charged particle in the high $|\eta|$ range, ii) there is a appreciable sensitivity to different tunes and iii) a big sensitivity to the regularization parameter P_{t0}. And finally the not well understood behavior of the not linear rise on multiplicity for pileup events is something remarkable for a further studies.

6 Acknowledgment

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