DEUTSCHES ELEKTRONEN SYNCHROTRON

Summer Students Program 2013

Monte Carlo study of the underlying event in $b\bar{b}$ pair production with the CMS detector at the LHC

Yasiel Delabat Díaz (CUB)
Supervisor: Paolo Gunnellini
DESY - CMS Group

Abstract:

The study of the underlying event in $b\bar{b}$ pair production has been performed using a new Rivet routine and Pythia 6 as event generator. Some results and comparison for inclusive jet and b-jet cross section measurements in pp collisions at $\sqrt{s} = 7\ TeV$ are also shown for two different Pythia tunes (AMBT and Z2). At the end a comparison between the UE in the transverse region for $b\bar{b}$ pair production and already measured Drell-Yan and hadronic events is presented.

Table of Contents:

INTRODUCTION 3

1. METHODS 6

1.1. Monte Carlo generators. 6

1.2. The UE characterization. 6

1.3. The UE Rivet routine. 7

2. RESULTS AND DISCUSSION 9

2.1. CMS_2011_S9086218 and CMS_2012_I1089835 cross section routines. 9

2.2. The UE routine. 10

CONCLUSIONS 15

REFERENCES 16

Introduction

The basis for understanding hadronic collisions at high energy is provided by the QCD improved parton model. In this framework each hadron is described as a collection of essentially free elementary constituents. The interactions between constituents belonging to different colliding hadrons are the seeds of the complicated process which eventually leads to the particles observed in the detector. Due to the composite nature of hadrons, it is possible to have multiple parton hard-scatterings, i.e. events in which two or more distinct hard parton interactions occur simultaneously in a single hadron-hadron collision [1].

Perturbation theory is a powerful tool for deriving the predictions of the standard model and its extensions in order to compare to experimental results. When strongly interacting particles are involved, perturbation theory becomes relevant for a momentum scale Q larger than 1 GeV. Then, one can expand the theoretical quantities for the short distance part of the reaction in powers of $\alpha_S(Q)$, which is small for large Q. The particles continue to interact at long distances, but for suitable types of experiments the long distance effects in the final state can be neglected while the long distance effects in the initial state can be factorized into parton distribution functions that describe the distributions of the partons in the incoming hadrons. This works if the measurement is only weakly affected by long distance interactions in the final state. Examples include the inclusive production of very heavy particles and the production of (suitably defined) jets of light particles [2].

The simplest sort of calculation for this purpose consists of calculating the hard process cross section at the lowest order in α_S, call it α_S^B, at which it occurs. For example, for two-jet production in hadron-hadron collisions, B = 2 while for three-jet production in electron - positron annihilation B = 1. This kind of lowest order (LO) calculation is simple, but leaves out numerically significant contributions. Corrections from higher order graphs are often found to be 50% of the lowest order result. For this reason, one often performs a next-to-leading order (NLO) calculation, including terms proportional to α_S^B and α_S^{B+1}. Then the estimated error from yet higher order terms (which are usually unknown) is typically smaller than 10% [2].

When a pair of quark-antiquark ($q\bar{q}$) separates by distances of about 1fm (from their formation point) α_S becomes large; that is, the colour interaction between the $q\bar{q}$ pair become truly strong, and these violent forces decelerate the quarks. The decelerated quarks radiate hadrons (mostly light π-mesons) just like a decelerated charge emits photons by bremsstrahlung. The original quark is never seen in its “free” state; only these π-mesons and other (colourless) hadrons hit the detector. The separating $q\bar{q}$ stretches the colour lines of force until the increasing potential energy is sufficient to create another $q\bar{q}$ pair with lower net energy despite the penalty of providing the extra $q\bar{q}$ mass. The outgoing quark and antiquark continue on their way further stretching the colour lines. More $q\bar{q}$ are produced until eventually their kinetic energy is degraded into clusters of quarks and gluons, each of which has zero net colour and low internal momentum, and therefore very strong colour coupling. This coupling turn them into the hadrons forming the two (or more) “jets” of particles traveling more or less in the direction of the original quark and antiquark. This is the way in which jets are formed and it´s called “hadronization” [3]. If this jets are produced by heavy flavoured quarks, like charm (c) or bottom (b), then it’s said that c or b jets were produced.

The b-jets are produced primarily through the higher order processes of flavour excitations (FEX) and gluon splitting (GS), and to a smaller extent by the leading order (LO) process of flavour creation (FC) (Fig. 1).

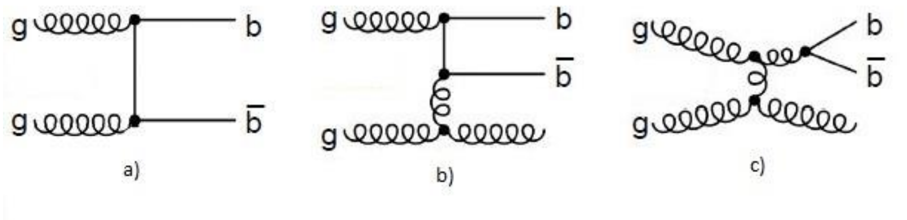

Fig 1. Feynman diagrams for the different LO and NLO b-jets production processes: a) flavour creation (FC), b) flavour excitation (FEX), and c) gluon splitting.

In order to find “new” physics at a hadron - hadron collider it is essential to have Monte Carlo models that simulate accurately the “ordinary” QCD events. To do this one must not only have a good model of the hard scattering part of the process, but also of the UE. The “hard scattering” component of the event consists of particles that result from the hadronization of the two outgoing partons (i.e. the initial two “jets”) along with the particles that arise from initial and final state radiation (i.e. multijets). The “underlying event” consists of particles that arise from the “beam-beam remnants” and from multiple parton interactions (MPI) [4].

In the presence of a hard process, characterized by particles or clusters of particles with a large transverse momentum p_T with respect to the beam direction, the final state of hadron-hadron interactions can be described as the superposition of several contributions: products of the partonic hard scattering with the highest p_T, including initial and final state radiation; hadrons produced in additional MPI; “beam-beam remnants” (BBR) resulting from the hadronization of the partonic constituents that did not participate in other scatterings. Products of MPI and BBR form the UE, which is difficult to separate from initial and final state radiation [1].

A complete description of hadronic activity in high energy collisions requires understanding of the UE, as it constitutes the unavoidable background to most observables. From an experimental point of view, the UE gathers all the activity accompanying the actual hard scattering one is interested in measuring. In this sense the UE consists of MPI and the interactions between constituents of beam remnants, left behind after the scattered partons have been pulled out. [1]

The UE is an unavoidable background to most collider observables and a good understanding of it will lead to more precise measurements in the future. For example, at the LHC both the inclusive jet cross section and the b-jet cross section depend sensitively on the UE [4]. Therefore the main objective of this work is to study the UE particularly in $b\bar{b}$ pair production. In order to do that other two analyses of inclusive jet and b-jet cross section for pp collisions at $\sqrt{s} = 7\ TeV$ are carried out.

This report is arranged in the following way: in Chapter 1 (*Methods*) are described some general characteristics of the used MC generator and the code interface, as well as the basic procedure for constructing the UE analysis; Chapter 2 (*Results and discussion*) shows the main results along with a short discussion of the most important aspects; finally, in the *Conclusions* is given an overview of the most important results and its significance.

1. Methods

1.1. Monte Carlo generators.

In order to achieve a better understanding of the physics behind those complex events produced in today´s large colliders, different MC generators and tunings can be used. These are very useful and powerful tools for the analysis of very complicated processes and are widely used in Nuclear and High Energy Physics. The task of a Monte Carlo event generator is to calculate everything that happens in a high energy collision, from the hard short-distance physics to the long wavelengths of hadronization and hadron decays [5].

The Pythia event generator can be used to generate high-energy-physics "events", i.e. sets of outgoing particles produced in the interactions between two incoming particles. The objective is to provide as accurate as possible a representation of event properties in a wide range of reactions, within and beyond the Standard Model, with emphasis on those where strong interactions play a role, directly or indirectly, and therefore multihadronic final states are produced. Detailed insights of physics behind this multihadronic final states are not quite well described by the perturbation theory but the program is based on a combination of analytical results and various QCD-based models that is able to give a reasonable description of several observables [6].

The Rivet project (Robust Independent Validation of Experiment and Theory) is a toolkit for validation of Monte Carlo event generators. Using a computationally efficient model for observable computations (known as the "projections" system), Rivet provides a set of experimental analyses useful for generator sanity checks, as well as a convenient infrastructure for adding new analyses. The work at the Monte Carlo level for this project was carried out by using Rivet. Pythia.6.246 was used as event generator for the analysis.

1.2. The UE characterization.

Measurements of UE have been performed in hadronic events as a function of the leading track and in Drell-Yan events as a function of the dimuon p_T. Now it's our interest to measure UE as a function of the leading jet p_T in $b\bar{b}$ events. To achieve a complete characterization of UE in that way we could divide a set of observables in different regions according to the azimuthal angle between charged particles in the final state and the "leading" b-jet (here we don´t distinguish between b and b-bar jets).

At the detector level, charged particles are observed as tracks in the inner tracking system. The direction of the b-jet with the largest p_T in the event (referred to as the "leading" b-jet) is used to define regions of the $\eta - \phi$ plane which have different sensitivities to the

UE. The axis given by the leading b-jet is well-defined for all events, and is highly correlated with the axis of the hard scattering in high-p_T events. As illustrated in Fig. 2, the azimuthal angular difference between charged tracks and the leading b-jet, $|\Delta\phi| = |\phi - \phi_{leading\ b-jet}|$, is used to define the following three azimuthal regions [1]:

- $|\Delta\phi| < 60°$, the "toward region".
- $60° < |\Delta\phi| < 120°$, the "transverse region".
- $|\Delta\phi| > 120°$, the "away region".

The transverse regions are most sensitive to the underlying event, since they are generally perpendicular to the axis of hardest scattering.

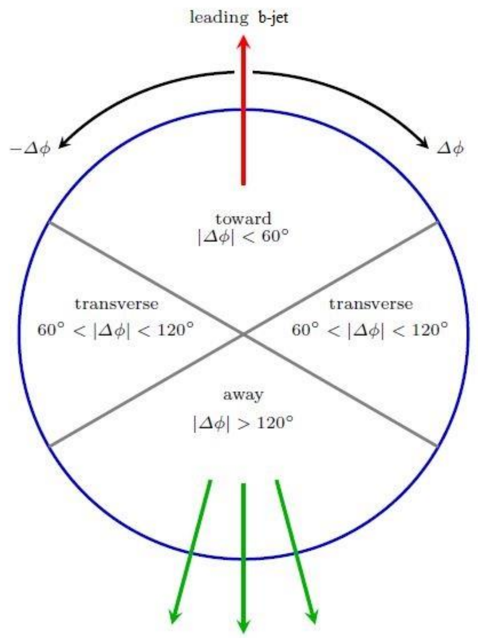

Fig 2. Definition of regions in the azimuthal angle with respect to the leading b-jet.

In this way it's then possible to describe efficiently the UE by looking at the observables in the different regions and trying to separate it from the hard scattering part.

1.3. The UE Rivet routine.

For now on our main goal will be to produce a Rivet routine capable of take into account different processes in the $b\bar{b}$ jets production as well as the underlying events that came up. The results could thus be compared with early experimental result in order to contribute to a better understanding of the physical meaning of them.

Basically we´ll analyse a set of observables such as final state charged particles Multiplicity, $\Delta\phi$, and $\sum p_T$ in order to complete the picture of the UE in the $b\bar{b}$ pair production in the CMS detector at the LHC.

The new routine created for describing this events are composed mainly by three projections:

- *FinalState*
- *ChargedFinalState* ($|\eta| \leq 2.5$, $p_T > 0.1\ GeV$)
- *FastJets (algorithm: ANTIKT, R=0.5).*

As b-jets selection criteria we'll require at least two jets with $p_T > 10\ GeV$. The criteria for selecting the charged particles for filling the different $\Delta\phi$ of them with respect to the leading b-jet was $|\eta| \leq 2.5$ and $p_T > 0.1\ GeV$. The charged particles inside the b-jets are not considered.

Since there is no available experimental data so far for this measurement, in order to check the description of the simulation for the light and heavy flavour sector, the predicted distributions of jet transverse momenta have first been compared with the experimental results from CMS. The measurements are implemented in two routines: CMS_2011_S9086218 (Validated and already included in the Rivet analyses list) and CMS_2012_I1089835 dealing respectively with inclusive jet and inclusive b-jet cross section measurements in pp collisions at $\sqrt{s} = 7\ TeV$ [7, 8].

2. Results and discussion

2.1. CMS_2011_S9086218 and CMS_2012_I1089835 cross section routines.

The firs routine used for testing the analysis reliability deals with the Inclusive jet cross section in pp collision at $\sqrt{s} = 7\,TeV$. This routine is divided into 6 different pseudorapidity regions:

i. $0.0 < |\eta| < 0.5$

ii. $0.5 < |\eta| < 1.0$

iii. $1.0 < |\eta| < 1.5$

iv. $1.5 < |\eta| < 2.0$

v. $2.0 < |\eta| < 2.5$

vi. $2.5 < |\eta| < 3.0$

The jet reconstruction algorithm used was the ANTIKT (R=0.5) and the p_T of the jets was recorded in a range between 18 and 1100 GeV.

It was also interesting to test the tune dependence of this analysis. That was done by using two tunes: AMBT and Z2. In figure 3 we can see some results for this routine. It´s evident that for both AMBT and Z2 tunes the Monte Carlo generated data fit very well with the CMS experimental data for the inclusive jet cross section. Also we can see how Z2 offers better agreement with the data especially for low p_T values.

The second routine used deals with inclusive b-jet cross section in pp collisions at $\sqrt{s} = 7\,TeV$. This routine is also divided into different pseudorapidity regions, in this case only 5:

i. $0.0 < |\eta| < 0.5$

ii. $0.5 < |\eta| < 1.0$

iii. $1.0 < |\eta| < 1.5$

iv. $1.5 < |\eta| < 2.0$

v. $2.0 < |\eta| < 2.2$

The b-jet reconstruction algorithm and the p_T range is the same as the first routine. The results for this routine are shown in figure 4. Again the results with both AMBT and Z2 tunes are very good.

According to the good results obtained with this preliminary tests we can ensure the reliability of the results coming out the routine for the analysis of the UE in $b\bar{b}$ pair production in pp collisions at $\sqrt{s} = 7\ TeV$.

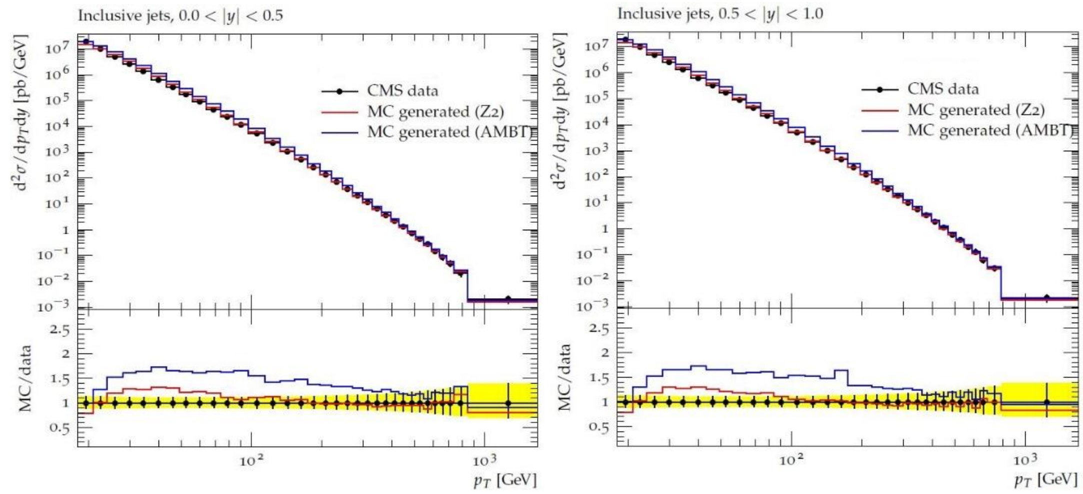

Fig 3. Plots for the inclusive jet cross section in pp collisions at $\sqrt{s} = 7\ TeV$. Comparison between experimental and MC generated data for AMBT and Z2 tunes.

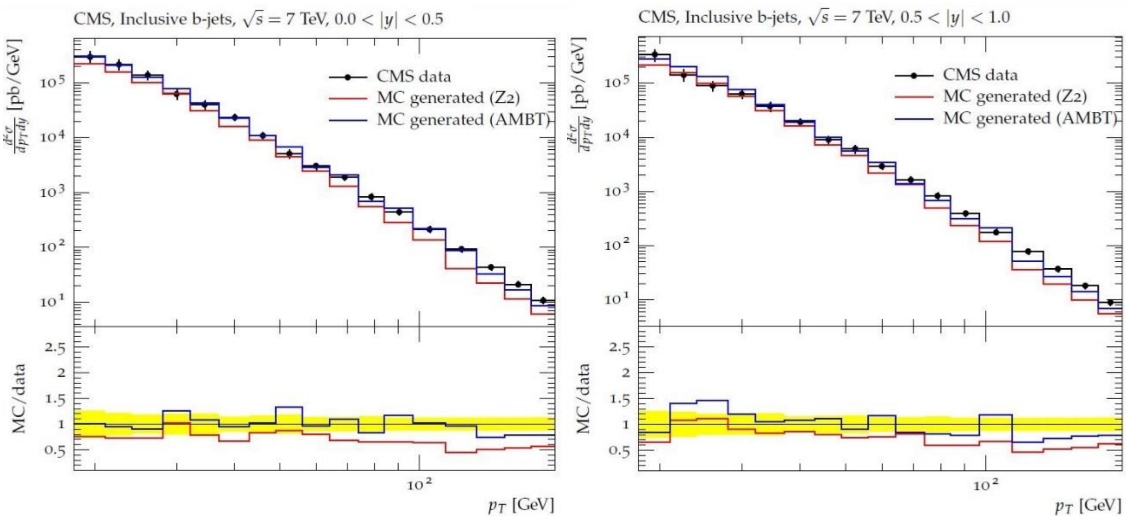

Fig 4. Plots for the inclusive b-jet cross section in pp collisions at $\sqrt{s} = 7\ TeV$. Comparison between experimental and MC generated data for AMBT and Z2 tunes.

2.2. **The UE routine**.

The study of the UE in $b\bar{b}$ pair production was performed using a new Rivet routine as described in 1.3. A more detailed description of this routine can be found at the end of this report. Figure 5 shows the $\Delta\phi$ distribution for the leading and sub leading b-jets. With all the tune parameters turned off, that is, MPI and parton shower (PS) turned off (MSTP(81) =20, PARP(61) = PARP(71)=0), we can see that, as expected, the leading and sub leading jets have a "back-to-back" distribution, while turning on all the parameters (playing only with the MPI on/off) smears the "back-to-back" configuration down to low $\Delta\phi$ values due to the PS and MPI contributions.

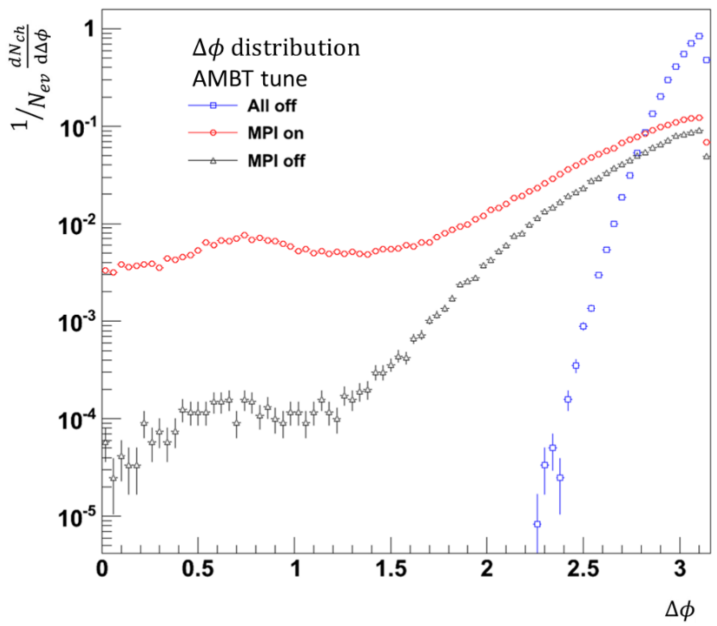

Fig 5. $\Delta\phi$ distribution for the leading and sub leading b-jets for AMBT tune.

Forward on, using the region distribution presented in 1.2, it was interesting to study the multiplicity and $\sum p_T$ distributions for the charged particles for the MPI on case. Such distributions are shown in figure 6. As expected, both Multiplicity and $\sum p_T$ show similar values in the toward and away regions due to the fact that these regions contain the hard scattering objects, while in the transverse region we can see slightly lower values.

Another comparison can be made between the multiplicity and $\sum p_T$ of the charged particles as a function of the leading b-jet p_T switching MPI on and off. This study is shown in figures 7 and 8 respectively. In this case we can see how in the transverse region both multiplicity and $\sum p_T$ present a nearly flat distribution, this is due to the fact that MPI contribution is already saturated at this scale. The effect of switching MPI on and off is, as expected, a rise in the multiplicity and $\sum p_T$ values.

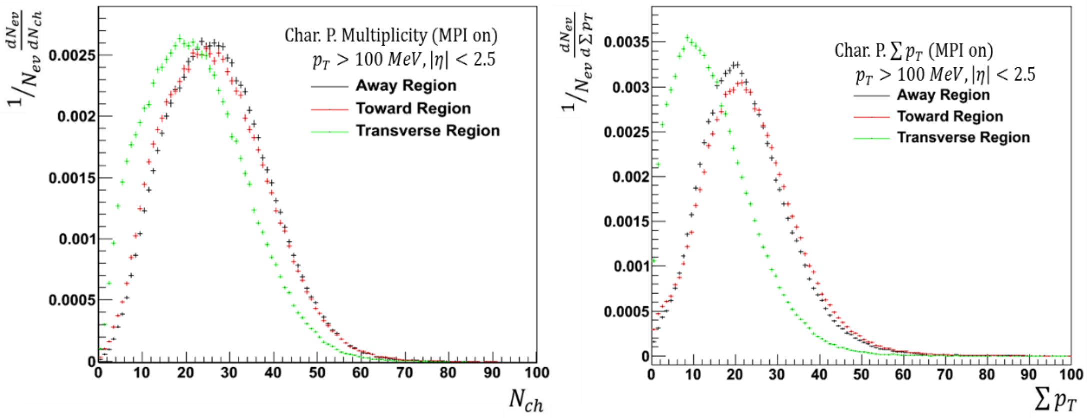

Fig 6. Charged particles multiplicity and charged particles p_T sum distributions for AMBT with MPI on.

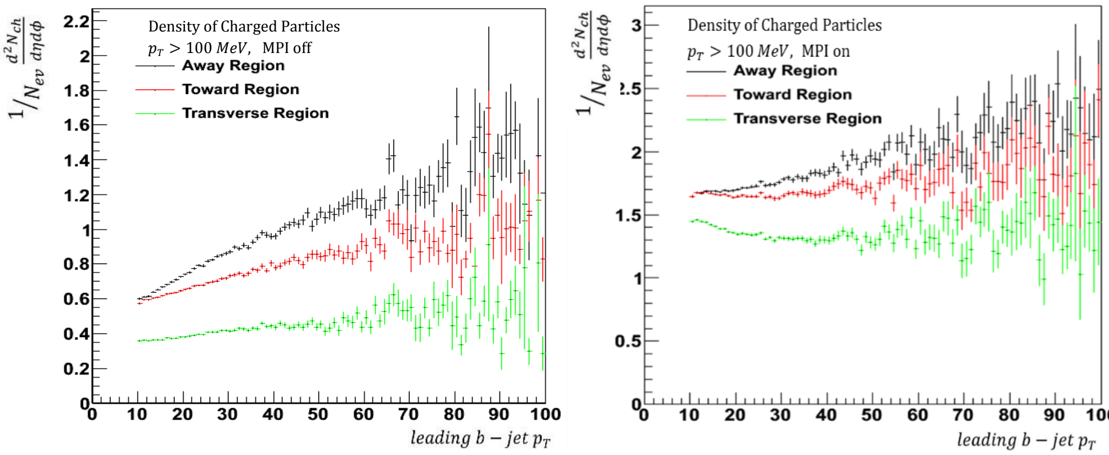

Fig 7. Charged particles multiplicity for the three $\Delta\phi$ regions as a function of the leading b-jet p_T: MPI off (left) and MPI on (right).

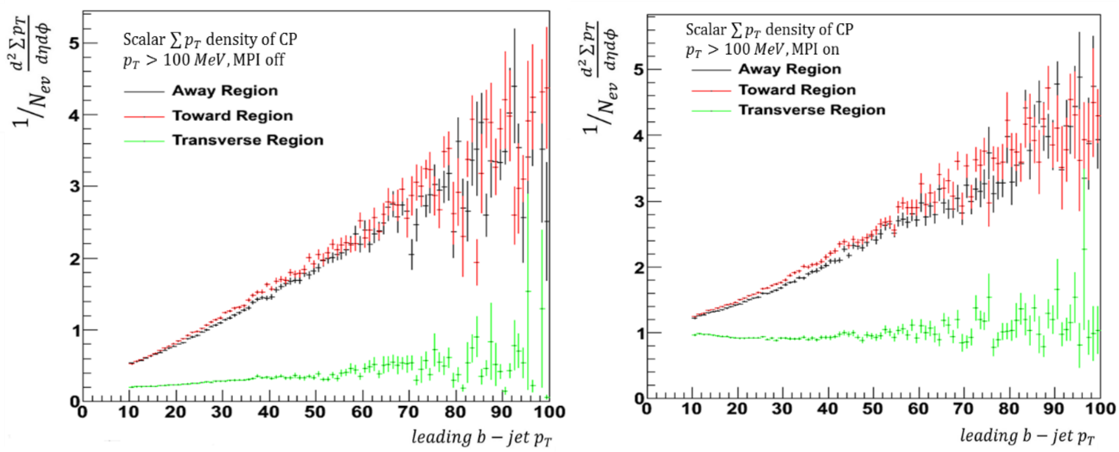

Fig 8. P_T sum for the three $\Delta\phi$ regions as a function of the leading b-jet p_T: MPI off (left) and MPI on (right).

Finally, in order to have some idea about how good or reliable our results were, a comparison between multiplicity and $\sum p_T$ of the charged particles for different events was carried out (figures 9 and 10 respectively). Here we compare UE behaviour only for transverse region observables in $b\bar{b}$ pair production as a function of the leading b-jet p_T, for Drell-Yan events as a function of the dimuon p_T and for hadronic events as a function of the leading track p_T. The results are quite similar despite the fact that for the charged particles density in the $b\bar{b}$ pair production the values are higher than for the rest of the events. This might be due to the fact that in the routine for UE in $b\bar{b}$ pair production we required a charged particles p_T above 100 MeV while for the Drell-Yan and hadronic events this threshold is at 500 MeV, consequently we are counting more charged particles in $b\bar{b}$ pair production than in the rest of the events.

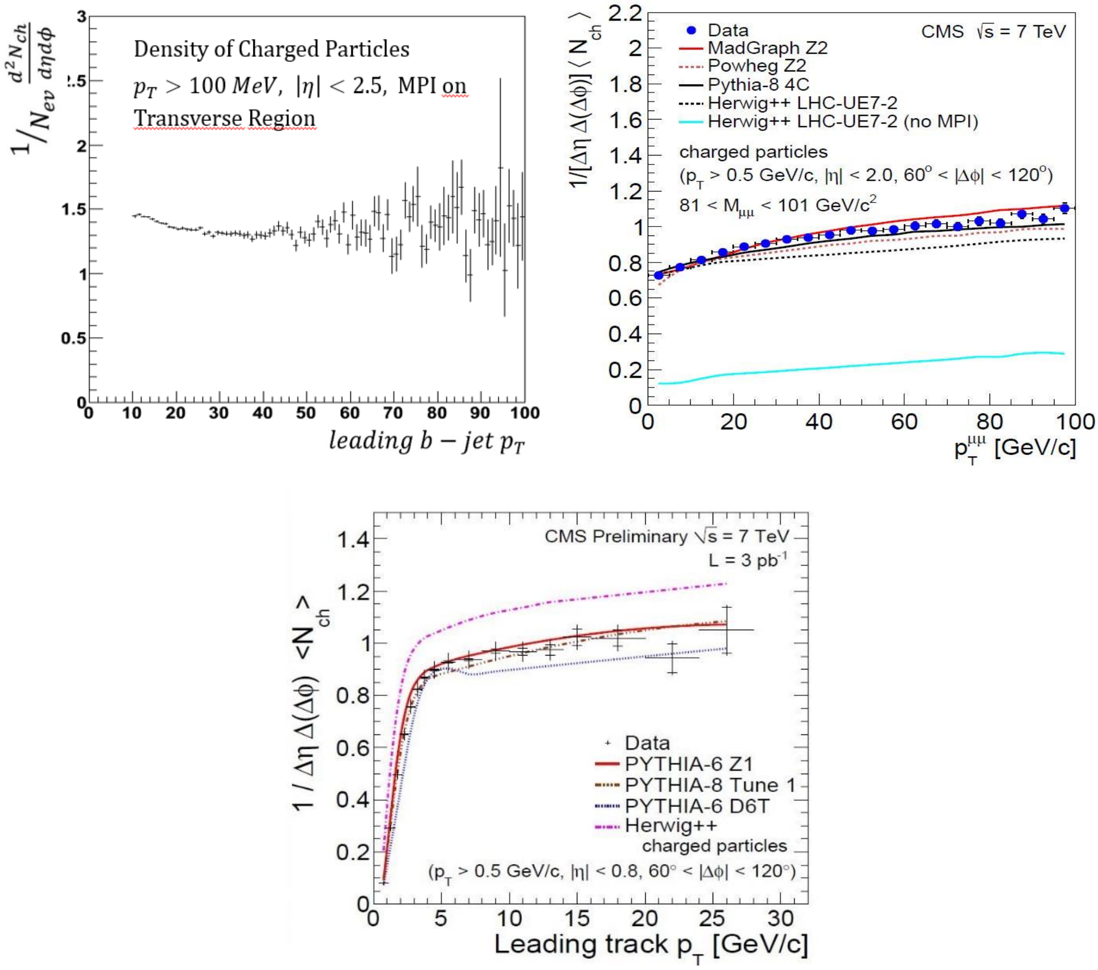

Fig 9. Transverse region multiplicity distribution for UE in three different kind of events: $b\bar{b}$ pair production, Drell-Yan and hadronic event [9, 10].

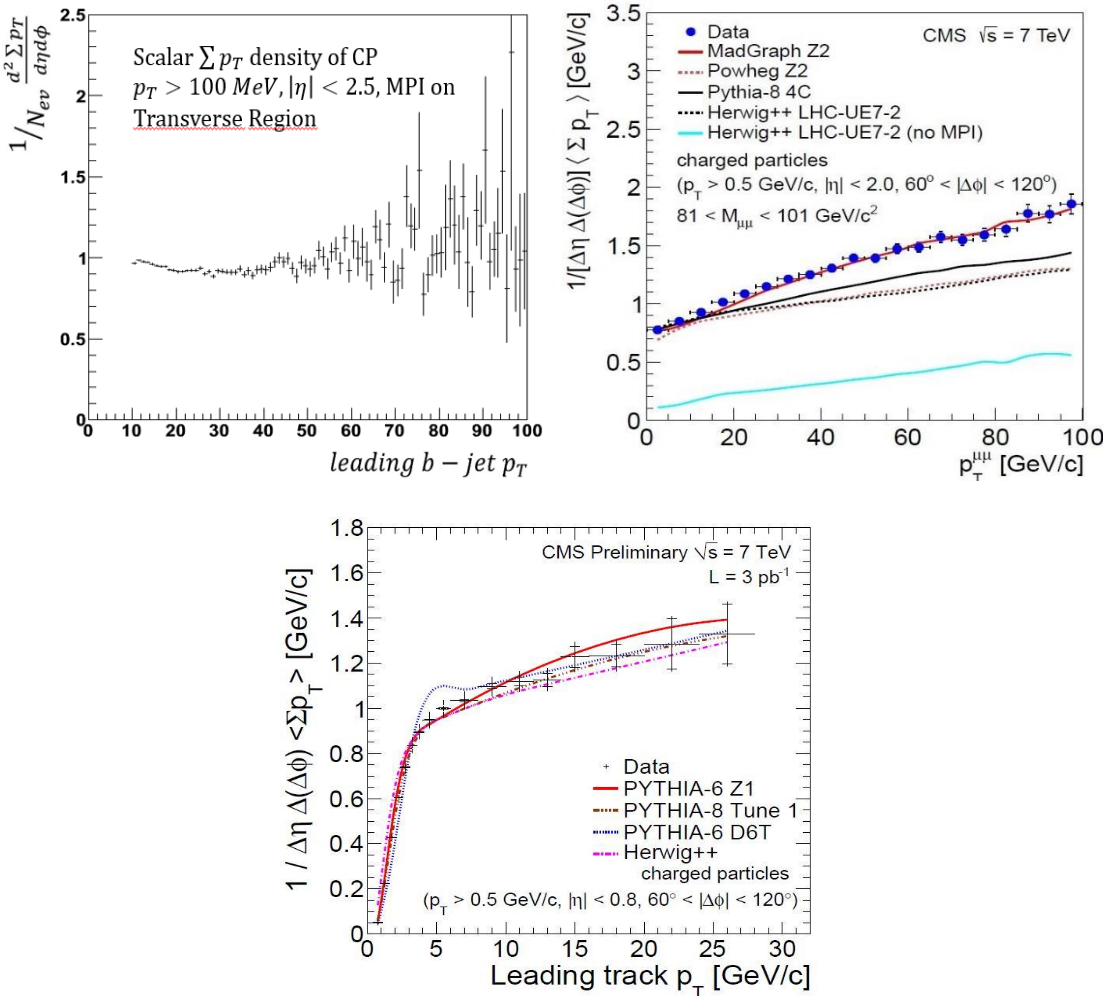

Fig 10. Transverse region p_T sum distribution for UE in three different kind of events: $b\bar{b}$ pair production, Drell-Yan and hadronic event [9, 10].

Conclusions

The study of UE in $b\bar{b}$ pair production for pp collisions at $\sqrt{s} = 7\ TeV$ has been carried out using a new Rivet routine with emphasis in three observables: $\Delta\phi$ distribution between the leading and sub leading b-jets, charged particles Multiplicity and $\sum p_T$ as a function of the leading b-jet p_T.

Due to the lack of experimental data to compare with, two additional routines were used as "validating routines" in order to ensure the reliability of the previous results. A comparison between two Pythia tunes (AMBT and Z2) was made; Z2 resulted to give the best description of the inclusive jet cross section.

The obtained results with the UE analysis routine have exhibited similar features to different kinds of hard scattering. In particular, the comparison between UE for bb pair production and Drell-Yan and hadronic events showed a good agreement.

References

[1]. CDF Collaboration (Field, R.D. for the collaboration) (2006). Studying the underlying event at CDF. *Conf.Proc.* C060726 581-584 FERMILAB-CONF-06-409-E

[2]. Halsen, F. & Martin, A. D. (1984). Quarks and leptons: an introductory course in modern Particle Physics. New York. John Wiley & Sons.

[3]. Krämer, M. & Soper, D. E. (2004). Next-to-leading order QCD calculations with parton showers I: collinear singularities. *Phys.Rev*. D69 (2004) 054019 arXiv:hep-ph/0306222v5

[4]. P. Bartalini et al. (2011). Multi-Parton Interactions at the LHC. *EPJ*. 2 - 4. arXiv:1111.0469v2

[5]. Sjöstrand, T., Mrenna, S., Skands, P. Z. (2006). PYTHIA 6.4:Physics and Manual. *JHEP 0605:026.* arXiv:hep-ph/0603175v2.

[6]. Skands, P. Z. (2012). *Introduction to QCD*. Lectures given at TASI 2012. Theoretical Physics, CERN, 1211 Geneva 23, Switzerland arXiv:1207.2389v1.

[7]. CMS Collaboration (Chatrchyan, Serguei et al.) (2012). Inclusive b-jet production in pp collisions at $\sqrt{s}$ =7 TeV *JHEP 1204 084* arXiv:1202.4617.

[8]. CMS Collaboration (Chatrchyan, Serguei et al.) (2011). Measurement of the Inclusive Jet Cross Section in pp Collisions at $\sqrt{s}$ =7 TeV. *Phys.Rev.Lett. 107 132001* arXiv:1106.0208.

[9]. CMS Collaboration (2012). Measurement of the Underlying Event Activity at the LHC at 7 TeV and Comparison with 0.9 TeV. *CMS-PAS-FSQ-12-020*.

[10]. CMS Collaboration (Chatrchyan, Serguei et al.) (2012). *Eur.Phys.J. C72 2080* arXiv:1204.1411.