Underlying events in $p + p$ collisions at LHC energies

András G. Agócs[1,2,a], Gergely G. Barnaföldi[1], and Péter Lévai[1]

[1] KFKI Research Institute for Particle and Nuclear Physics of the HAS,
29-33 Konkoly-Thege M. Str. H-1121 Budapest, Hungary
[2] Eötvös University,
1/A Pázmány Péter Sétány, H-1117 Budapest, Hungary

Abstract. General properties of hadron production are investigated in proton-proton collisions at LHC energies. We are interested in the characteristics of hadron production outside the identified jet cones. We improve earlier definitions and introduce surrounding rings/belts around the cone of identified jets. In this way even multiple jet events can be studied in details. We define the underlying event as collected hadrons from outside jet cones and outside surrounding belts, and investigate the features of these hadrons. We use a PYTHIA generated data sample of proton-proton collisions at $\sqrt{s} = 7$ TeV. This data sample is analysed by our new method and the widely applied CDF method. Angular correlations and momentum distributions have been studied and the obtained results are compared and discussed.

1 Introduction

The production of hadron showers with large transverse energy (named as "jets") is one of the most interesting phenomena in high energy proton-proton (and hadron-hadron) collisions. Jet production is explained by the interaction of the ingredients of protons, namely partons: quarks, antiquarks, and gluons. The perturbativ quantum chromodynamics (pQCD) improved parton model [1] can describe the momentum distribution of produced secondary partons very successfully. The hadronization of the secondary partons is followed by parton fragmentation functions and the resulted hadron showers carry the energy and momenta of the original partons. Jet analysis efforts are aiming the identification of these original partons and to determine their properties. However, during proton-proton (pp) collisions the leading jet production is only one part of the activity, in parallel many partonic subprocesses take place with smaller interaction energy.

First of all, multiple parton-parton collisions with relatively large momentum exchange can happen with a reasonable probability generating the problem of multiple-jet identification. At LHC energies these multiple-jet events have a reasonable yield, their investigation will become one of the focus study of strong interaction in forthcoming LHC experiments. These interactions form a background event, and it is very important to separate these jets properly from the leading jets, which is not an easy task. The basic problem is the overlap of two (or more) hadron showers and the uncertainties on jet identifications. Under a limiting momenta the separation can not be done, even more the reconstruction slightly depends on the applied method, especially with decreasing parton energies.

If momentum exchange become small, then the background events can not be separated into jets, but considered together. This is the "underlying event" (UE), where the application of pQCD is ambiguous and phenomenological descriptions appears to catch certain features of the hadron ensamble. The underlying event is important especially in such a cases, when large hadron multiplicities appear in the final state, leaving open the question if these extra hadrons are produced during jet fragmentation or in the center of the collisions with small momentum excange. In this latter case we expect increasing hadron multiplicities with increasing energy even in pp collisions, which indicates the enhancement of entropy production connected to low energy parton-parton interactions. This hadron ensamble could display collective behaviours including thermalization or the appearance of different flow phenomena. The characteristics of the UE event in pp collisions can be connected to the study of heavy ion collisions, where the UE state is dominantly collective and jet-matter effects can be investigated. Our aim is to collect information about the jets and UE event, and to study their measurable features if jet-UE interaction appears.

Underlying event was originally defined by the CDF Collaboration [2] at the energy of TEVATRON. Since multiple jet events were very rare, then UE has denoted the remaining hadrons of a proton-antiproton ($p\bar{p}$) collisions, after leading jets were identified and hadrons of jet cones were removed from the whole event. The CDF definition of the underlying event is a simple tool. However, with this definition we are unable to analyze multiple jet production. We have increased the quality of the extracted information by a modified definition introducing multiple surrounding belts (SB) around identified jets [3,4]. This new definition immediately leads to a more sophisticated analysis of UE.

[a] e-mail: agocs@rmki.kfki.hu

We have already performed analysis with the new SB-method and summarized our results in Ref. [5]. However, many question remained open. Especially the discussion on quantitative differences between the consequences of CDF-definition and the SB-method is missing.

Here we focus on this comparision. We recall the original CDF-based and our SB-based definition of the UE and compare them qualitatively. We perform quantitative calculations and compare several physical quantities: (i) the average hadron multiplicities within the defined areas relative to the total event multiplicities; (ii) simple geometrical properties such as azimuthal angle distributions and pseudorapidity distributions in the close-to-midrapidity regions; (iii) transverse momentum distributions in the discussed regions.

We are interested in these physical quantities, because we want to use them to look jet-matter interactions and other collective effects in nucleus-nucleus (*AA*) collisions. Such investigation demands better understanding of UE events in *pp* collisions, since UE can serve as baseline for the detailed study of *AA* results.

We have performed our analysis on a data sample generated by PYTHIA 6.2 [6] for *pp* collisions at 7 TeV. The jets have been identified by the cone-based UA1 jet finder algorithm [7], setting jet cone angle $R = 0.4$.

2 Generalized definition of the UE

The basic definition of underlying events is very simple: remove all particles connected to identified jets from the total event and the wanted UE consists of the remaining particles. This kind of definition may have some dependence on the applied jet-finding algorithm (and its parameters), especially on the momentum threshold of identified jets. However, if we trust in the correctness of recent state-of-the-art jet-finding algorithms (see Refs. [8,9]), then the remaining particles must be unambiguously defined and we can focus on the properties of this particle ensamble.

Historically the CDF collaboration was the first to establish a plausible definition to determine UE [2], which was commonly used for decades in various analysis. This CDF-definition corresponds to jet identification in one-jet events, where the second jet is assumed to move automatically into the away side. The CDF event geometry can be fixed easily, since the position of the leading jet defines the *toward region*, and the *away region* will be chosen respectively. The left side of Fig. 1 displays this definition.

Our concept was to improve the CDF-based definition on the following points:

- to develop an new UE definition, which is strongly connected to the identified jets (excluding all hadrons from all identified jets), independently on the number of jets. Thus it can be used for multijet events, also.
- to gain the capability of investigating the surrounding areas around identified jets, without major changes in jet-finding parameters. Thus we can study *pp* and *AA* collisions in the same frame and compare the obtained results, directly.

These requirements led us to the definition of surrounding belts (SB) around jet cones. Thus the UE is defined via excluding hadrons both from jet cones and SBs. We are using jet-finding algorithms to define jets and jet-cones, than the concentrical surrounding belts are selected by fixing the width of the belts. The correctness of jet finding algorithm can be easily checked by comparing the properties of hadrons inside jet cone and surrounding belts.

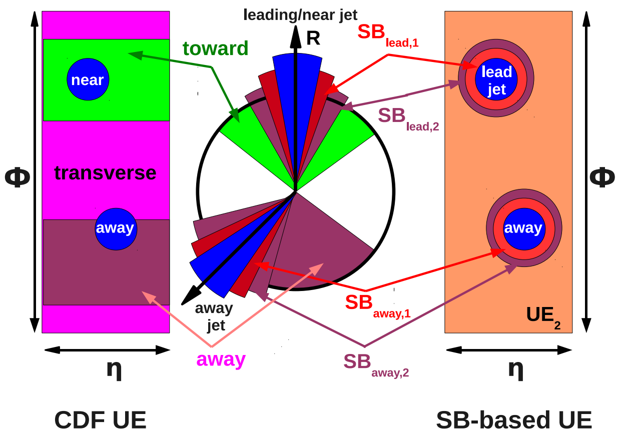

Fig. 1. ((*Color online*) The schematic view of the underlying event (UE) defined by the CDF-method (*left panel*) and the SB-method with surrounding belts (*right panel*). Detailed explanation can be found in the text and Ref. [5].

Fig. 1 serves for the visual comparison of the two definitions. The CDF-based definition is seen on the *left side*, the SB-based new definition is indicated on the *right side*. The two definitions can be summarized by means of the azimuthal angle, Φ, and (pseudo)rapidity, (η) y plane:

CDF-based definition of the UE is based on the subtraction of two areas of the whole measured acceptance: one around the identified near jet (*toward region*) and another to the opposite (*away*) direction. Both regions are $\Delta\Phi \times \Delta\eta$-slices of the measured acceptance around the near jet and to the opposite, with the full $\Delta\eta$ range and limited Φ-range, namely $\Delta\Phi = \pm 60^o$ in azimuth.

SB-based definition means the substraction of all hadrons connected to identified jets and their SB-areas. Each jet is characterized by an approximate dial-like area, around which concentric bands (or rings) are defined. If the jet cone angle, $R = \sqrt{\Delta\Phi^2 + \Delta\eta^2}$ is given, then a first 'SB_1' and a second 'SB_2' surrounding belt will be defined for all jets, where the thickness of δR_{SB1} and δR_{SB2} are introduced. Usually $\delta R_{SB1} = \delta R_{SB2} = 0.1$ at jet-cone values $R = [0.5, 1]$. It is easy to see that this UE definition is independent from the identified jets, even if we have more jets in one collision. Furthermore, increasing the δR_{SBi} values, similar (but not the same) area can be covered by the SB-method as by the original CDF-definition. In this way the covered areas of the two models can become close to be identical at large SB-thickness.

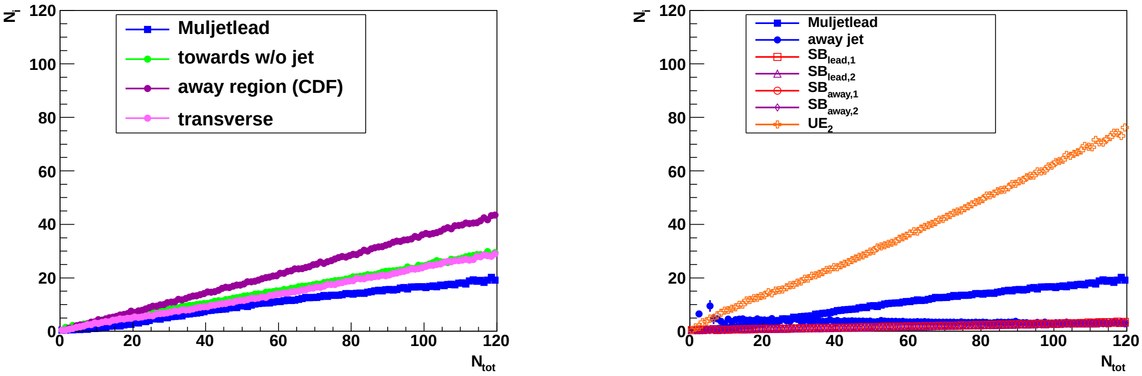

Fig. 2. (*Color online.*) The charged hadron multiplicities, N_i, of the selected areas depending on the total multiplicities of the events, N_{tot}. The CDF-based results are displayed on the left panel, SB-based results can be found on the right panel. Details can be found in the text.

3 Qualitative comparison of different UE sets

We have already performed an SB-based analysis of a simulated data set for pp collisions at 7 TeV and published the results in Ref. [5]. Here we extend this early investigation for a larger data set of 500 000 pp events created by PYTHIA-6 simulation [6], applying the Perugia tune [10]. This sample is similar to the LHC10e14 samplecreated at the ALICE experiment for 7 TeV pp collisions. In the available sample the jets are identified by the UA1 method [7]. We restrict our analysis to a limited sample, where the cuts of $p_{THardMin}$ = 10 GeV/c and $p_{THardMax}$ = 20 GeV/c have been applied. After these cuts we still had around 156 000 events, which contains at least one jet. All quantitative results displayed in this paper are extracted from this data sample.

3.1 Multiplicity dependences in both analysis

First we analyse the charged hadron multiplicities in the various regions of both geometrical definitions. We apply UA1 jet-finding algorithm to identify jets, than we collect the multiplicities in the different regions of the CDF-method and the SB-method. Since the statistics is higher than previously, then we expect results with higher precision than in Ref. [5].

In Fig. 2 we display the multiplicities, N_i of the different areas depending on the total multiplicities of the events. In the *left panel* the displayed results are obtained by the CDF-method. Here N_i refers to the following contributions: the multiplicities of the identified 'leading/near jet' (*blue squares*), the jet-excluded 'toward' area (*green dots*), the 'away' side area at the opposite direction (*purple dots*), and the CDF-defined UE yield (*pink dots*).

The *right panel* of Fig. 2 displays the multiplicities correspond to the SB-based definition of the underlying event and contains detailed information on more areas: the multiplicities of the identified leading jet (*blue squares*), the away side jet (*blue dots*), multiplicities for the surrounding belts, $SB_{lead,1}$, $SB_{lead,2}$, $SB_{away,1}$, and $SB_{away,2}$ (*open red squares, open purple triangles, open red circles, open purple diamonds* respectively). Finally *orange crosses* denote multiplicities for the newly defined underlying events, which collect hadrons outside all identified jets. We denote this quantity by UE_2. (Note, all color codes correspond to the areas of Fig 1.)

One can see in Fig. 2 that all multiplicities, N_i, increases linearly with the total multiplicity in the region N_{tot} < 120 in both cases. Applying the CDF-based definition, the away region gives the largest contribution, and the leading jet contribution is the smallest one. The transverse area (named as UE) yield an intermediate size contribution. Moreover, it is interesting to see, that after excluding the jet from the toward region, the remaining area has almost the same multiplicity as the underlying event. This shows the correctness of the jet finding algorithm and the "safety" of the CDF-based underlying event definition (e.g. 1/3 of the whole acceptance is far from any jet-contaminated areas).

The multiplicities with the SB-based definition differ from the results of the CDF-based analysis. The near side jet and away side jet have similar contribution, since jet-finding algorithm was working properly. The contributions from the belts, SB_i, have small multiplicities, since they cover very small areas. On the other hand, the contribution from the newly defined underlying event, UE_2 dominates the plot, since it covers almost the whole acceptance.

In general, the multiplicity fraction of the defined areas are almost proportional to the geometrical surface, only the jet-content part violates this dependence, as Fig. 2 displays. Thus, the SB-based UE_2 is characterized by larger multiplicity value than the CDF-based UE.

3.2 Test of geometry

On Fig. 3 we plotted the azimuth-angle (Φ) distribution of the selected areas for CDF-based (*left panel*) and SB-based (*right panel*) definitions. Here we used the color codes of Fig. 1 and Fig. 2.

Due to the geometrical roots of the underlying event definitions, the azimuth-angle distribution is clearly separated for the CDF-based definition but very complicated in

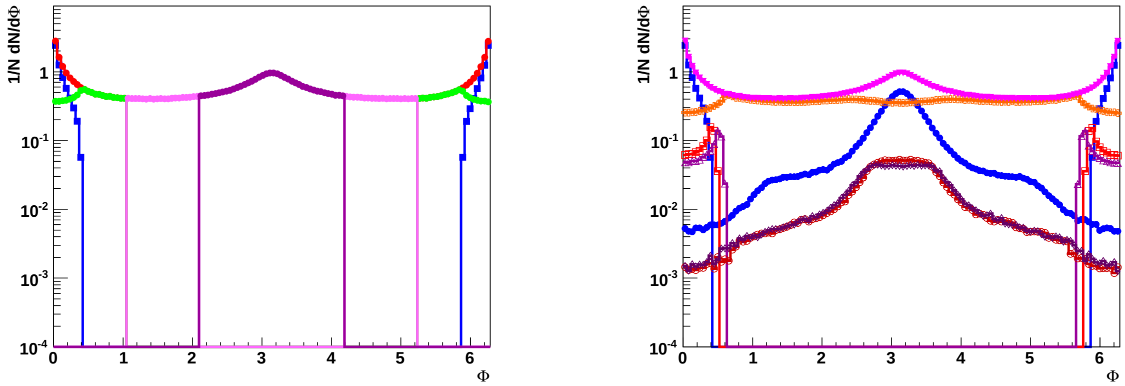

Fig. 3. (*Color online.*) The azimuthal angle (Φ) dependence of particle production in the CDF-based (*left panel*) and SB-based (*right panel*) analysis of UE. Details can be found in the text.

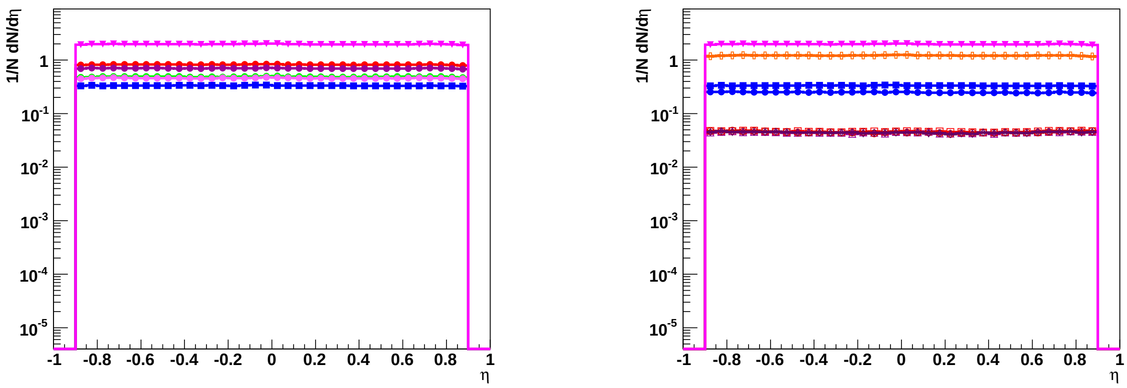

Fig. 4. (*Color online.*) The pseudorapidity (η) dependence in the CDF-based (*left panel*) and SB-based (*right panel*) analysis of UE. Details can be found in the text.

the SB-based case. The CDF-based results display a clear envelope curve including *red "wings"*. The UE yield — indicated by *magenta* — is almost flat. Opposite to the leading jet, at $\Phi \approx \pi$, the away side region is characterized by a well-defined Gaussian-like distribution.

One can see that the SB-based analysis is more sophisticated, it carries more information. The jet "wings" at the sides and the envelop curve is the same as the results from the CDF-based analysis. However, the yields from the away-side jet and surrounding belts $SB_{away,1}$ and $SB_{away,2}$ shows complex structure (*blue dots, purple diamonds and orange circles*). The validity of our underlying definition (UE_2)is supported by the appearance of a wide flat area in η (indicated by *orange crosses*), clearly spearated from jet cone and SB contributions.

On Fig. 3 the pseudorapidity distributions are shown for CDF-based (*left side*) and SB-based (*right side*) analysis. Since we have limited acceptance in the rapidity direction, we focus on the close-to-midrapidity regions: $\eta \in [-0.9; 0.9]$. Within this areas, both underlying event definitions yield flat rapidity distributions. Since particle yields correspond to the surface of the defined areas, thus SBs yields are small. However, the UE and UE_2 contributions dominate the yields.

3.3 The p_T-distribution for the selected areas

We are interested in the transverse momentum spectra of charged hadrons detected in the different areas of the CDF- and SB-setup. Fig. 5 displays results for $p_T \leq 60$ GeV/c. We can see relatively large difference between the CDF and SB cases. The *left panel* shows the CDF-based results, the color encoding corresponds to Fig. 1. The obtained spectra are quite similar for the different regions, a close to linear shift characterizes the differences, which is connected to the proper geometrical surface. Thus jet-excluded near and the UE areas (*pink and green dots*) display the smallest yield at high-p_T. The spectra of away side hadrons (*purple dots*) dominates the yields, but without any structure. It seems to us, the CDF-based underlying event definition generates separation between the spectra of the selected areas.

On the other hand, the SB-based definition results in a better separation for the different momentum distributions.

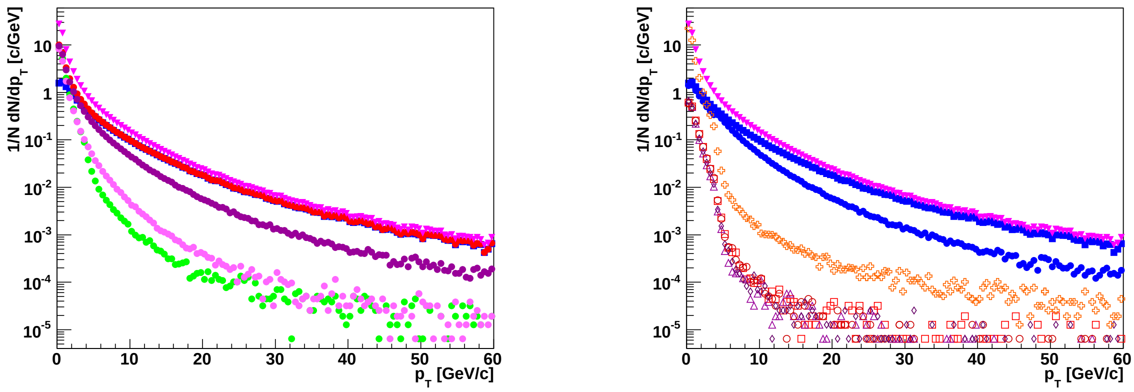

Fig. 5. (*Color online*) The transverse momentum spectra (p_T) for the CDF-based (*left panel*) and SB-based (*right panel*) underlying event and related geometrical regions. More details can be found in the text.

The transverse momentum spectra within the identified jet cone, plotted by *blue squares and points* for comparision and corresponds to the CDF-based definition. The underlying event has similar spectra, however the SB-based definition results in a more steeper distribution at lower-p_T values. Spectra for the surrounding belts have the lowest yields and starts together with the SB-defined underlying event spectra, but with a cut-off at $p_T \approx 10$ GeV/c.

4 Conclusions

We have studied underlying event definitions in proton-proton collisions at $\sqrt{s} = 7$ TeV. We have investigated and compared the multiplicities, azimuth-angle and pseudorapidity distributions, and transverse momentum spectra for the CDF-based and SB-defined regions.

We tested the multiplicity fraction of the defined regions and repeated our earlier study [5]. Using a larger data sample a clear separation of the undelying event has been found. Comparing the CDF-based and SB-based underlying event definitions the latter gives a better separation in sense of highest multiplicity relatively to the total multiplicits of the event, N_{tot}. This originates from the more sophysticated definition and the larger geometrical surface to be considered. Oppossite to this the original CDF-based definition does not give a good multplicity separation, since away, transverse and jet-excluded toward regions have similar multiplicity content.

A more clear explanation of the geometrical distribution is arising from the azimuth angle and pseudorapidity distribution. The CDF-based azimuth angle distribution is quite clear, it results in two small, almost flat Φ distribution of the UE. In the SB-setup, the obtained azimuth angle distributions are overlapping, but the whole underlying event region becomes a well defined background. Moreover, in the investigated close-to-midrapidity region, $|\eta| \lesssim 1$, the magnitude of the constant η distrubution is proportional to the area of the CDF- or SB-defined regions.

Finally, we compared the transverse momentum spectra for the different regions. The SB-method gives a more sophisticated separation of the charged hadron yields from different regions and its general use is much more supported to study the properties of the UE and any jet-matter interactions inside the surrounding belts.

Acknowledgments

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