Jets and Underlying Events at LHC Energies

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Abstract. Jet-matter interaction remains a central question and a theoretical challenge in heavy-ion physics and might become important in high-multiplicity events in proton-proton collisions at LHC energies. Full jet measurement at LHC offer the proper tool to investigate energy loss process and fragmentation of hard parton in the medium. Since jet reconstruction will be constrained to small cone sizes, then study of the connection between jets and surrounding environment provides a further possibility to extend our exploration. We study jets at $\sqrt{s} = 14$ TeV and $pp$ collisions at $\sqrt{s} = 7$ TeV. We analyze the flavor components in jet-like environments. We introduce a definition for surrounding cones/belts and investigate flavor dependence and correlation of different hadron species produced in jets. Here, we focus on proton-triggered correlations. Our analysis can be extended for heavy ion collisions.

1. Introduction

The state-of-the-art particle detectors and very-high energies reached at the Large Hadron Collider (LHC) opened a new window to create and investigate high momentum particle showers in hadron-hadron collisions. These showers originate from color partons and they are identified as jets. Jets were discovered in electron-positron ($e^-e^+$) collisions, where it was assumed: partons are travelling in QCD vacuum. However, in proton-proton and heavy-ion collisions partons are propagating in a color medium. The deconfined medium modifies the parton properties e.g. induces gluon radiation and parton energy loss [1]. This phenomena has been seen and investigated in details in heavy-ion collisions at RHIC energies [2, 3].

High-multiplicity proton-proton events may behave similarly displaying intense interaction between jets and the surrounding ‘matter’. Thus, study of jet energy loss and jet-matter interaction can be accomplished with the proper determination of the jets and the remaining background, the so called underlying events.

Generally speaking, underlying events (UE) contain particles originating from partons outside identified jet(s). The first ‘standard’ definition of UE was given by the CDF Collaboration at Fermilab [4]. In an earlier work we introduced surrounding belts (SB) around the cones of identified jets [5]. Here, we focused on properties of near and away side jets, and their surrounding regimes, especially hadron contents and correlations.

We display our recent results on the generalized definition of the underlying event. We analyzed mean-$p_T$ vs. multiplicity for the newly defined areas in case of $\sqrt{s} = 14$ TeV proton-proton collisions. We performed PYTHIA simulations for $\sqrt{s} = 7$ TeV $pp$ collisions. We used PYTHIA 6.4 [6] with ATLAS-CSC tune [7] for both cases and generated $\sim 20$ M minimum bias events. Furthermore, we have studied proton-triggered correlations in surrounding belts characterized by various radii and thicknesses at $\sqrt{s} = 7$ TeV.
2. Mean-\(p_T\) vs. multiplicity for the generalized UE

Transition area between jet cones and underlying event carries information about jet-matter interaction. The investigation of this area demands proper definitions and solid basis for quantitative analysis.

First we considered the mean transverse momenta vs. multiplicity in 14 TeV proton-proton collisions. The newly defined areas based on right panel of Fig. 1. Here, the main areas are highlighted: 'near' and 'away' refers for the the near- and away-side jets respectively. We marked the inner surrounding belt with 'SB1' and the outer 'SB2' for both near and away side jets. Based on this definition, the underlying event is everything outside the outer belts.

Hadron multiplicities can be given in each region however, for reference we used \(N_{UE2}\), which is the generalized underlying event area – outside both outer surrounding belts. We plotted the mean transverse \((\langle p_T \rangle)\) momenta of above areas as the function of \(N_{UE2}\) on the left panel of Fig. 1. The \((\langle p_T \rangle)\) for near- and away-side jet is drawn by full squares and full disks respectively. Mean-\(p_T\) for surrounding belts are plotted with open squares and open triangles for inner belts: 'SB1_{near}' and 'SB1_{away}'. Open circles and diamonds denote results on outer belts: 'SB2_{near}' and 'SB2_{away}'. Full triangles display the \(\langle p_T \rangle\) for the total event. Finally, we indicated \(\langle p_T \rangle\) for the underlying event with stars.

As we plotted on Fig. 1 jet-like events has high-\(\langle p_T \rangle\) values, with low multiplicity, due to the produced jets in the 14 TeV pp collisions. Mean \(p_T\)s for these jet-like events are falling quickly as the \(N_{UE2}\) multiplicity is increasing. In parallel, the \(\langle p_T \rangle\) for the total event has a similar structure. Surrounding belts have almost the flat value \(\langle p_T \rangle = 1\) GeV/c, practically at every \(N_{UE2}\) value. Testing the underlying event, \(\langle p_T \rangle_{UE}\) is increasing up to \(\sim 2\) GeV/c, indicating a 'mini-jet' like structure at high multiplicities is starting to play the role, as we pointed out in Ref. [5].
3. Geometrical setup for the analysis

The aim of our study is to map differences in surrounding belts, connected to near-side and away-side correlation peaks. Such differences carry information about hadronization processes and/or possible jet-matter interactions. The wanted differences can be amplified displaying the ratio of hadron yields in the different belts: SB1\text{near}/SB1\text{away} and SB2\text{near}/SB2\text{away}.

Following the illustration of Fig. 1, we define 3 different ‘geometrical’ sets to be analyzed:

**CDF-set**: $\Delta \phi_{\text{near}} = 0^\circ \pm 60^\circ$; $\Delta \phi_{\text{away}} = 180^\circ \pm 60^\circ$; $\Delta \phi_{SB1} = \Delta \phi_{SB2} = \pm 6^\circ$.

**R-set**: $\Delta \phi_{\text{near}} = 0^\circ \pm 30^\circ$; $\Delta \phi_{\text{away}} = 180^\circ \pm 30^\circ$; $\Delta \phi_{SB1} = \Delta \phi_{SB2} = \pm 6^\circ$.

**$\sigma$-set**: $\Delta \phi_{\text{near}} = 0^\circ \pm \sigma_{\text{near}}/2$; $\Delta \phi_{\text{away}} = 180^\circ \pm \sigma_{\text{away}}/2$; $\Delta \phi_{SB1} = \Delta \phi_{SB2} = \pm 6^\circ$.

The CDF-set is motivated by the original definition from CDF Collaboration [4]. The R-set is motivated by a smaller, jet-cone-like size. The $\sigma$-set is determined from PYTHIA simulations on correlations at 7 TeV at corresponding trigger and associated momentum regions. Here we will use $\sigma_{\text{near}} = 16.0^\circ$ and $\sigma_{\text{away}} = 19.5^\circ$ displayed on Fig. 1.

Comparing the above selections, the area of the underlying event is the smallest in the case of CDF-set, and it is the largest for $\sigma$-set. The widths of the surrounding belts ($6^\circ$) is a result of an optimalization to have proper statistics for analysis and comparison.

4. Correlation studies with charged hadron triggers

We have calculated the wanted ratios of SB1\text{near}/SB1\text{away} and SB2\text{near}/SB2\text{away} for all possible charged hadron triggers, namely choosing one of the identified hadrons ($\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$, $\bar{p}$) as trigger particle and extracting angular correlation with all other identified hadron species.

![Figure 2](image-url)  

**Figure 2.** Differences in the proton-triggered correlation functions, enhanced by ratios of surrounding belts, SB1\text{near}/SB1\text{away} and SB2\text{near}/SB2\text{away} as a function of transverse momentum of the associated hadrons, $p_{T,\text{assoc}}$. See text for details on legend. (Color online.)
Fig. 2 displays our results extracted from PYTHIA simulations for \( pp \) at 7 TeV, using proton trigger in the momentum window defined earlier. Inner belt ratios, \( SB_{1\text{near}}/SB_{1\text{away}} \) are marked by full squares for ‘CDF-set’, full disks for ‘R-set’, and full triangles for ‘\( \sigma \)-set’. Outer belt ratios, \( SB_{2\text{near}}/SB_{2\text{away}} \) are marked by open squares for ‘CDF-set’, open circles for ‘R-set’, and open triangles for ‘\( \sigma \)-set’. Further results for other identified hadron triggers can be visualized similarly, but we want to focus on proton trigger.

Results from ‘CDF-set’, indicated by full and open squares are close to be unity (no effect) in all correlations. This means we are testing homogeneous UE region far from correlation peaks.

Results from ‘R-set’, indicated by full and open circles go below unity for most of the hadrons (except antiprotons), because of the expected momentum conservation for leading hadrons. Antiprotons behave differently due to a strong correlation in baryon-antibaryon production closer to the correlation peaks. This effect is based on baryon number conservation. A slight difference can be already seen between the ratios from inner belt and outer belt.

In the case of ‘\( \sigma \)-set’ (full and open triangles) we are closer to the correlational peaks, but the results are very similar to the ‘R-set’, except the deviation in proton-antiprotons correlation is even more strong. Thus, we are really in the fragmentation region with very strong baryon-antibaryon correlation. A slight difference between the inner belt and outer belt can be seen, also.

Taking \( K^+ \) trigger we will see strong \( K^+-K^- \) correlation driven by strangeness conservation. The \( K^+-\)proton and \( K^+-\)antiproton correlations are just similar to e.g. \( K^+-\pi^+ \) ones.

5. Conclusions
We have investigated identified hadron correlations in \( pp \) collision at 7 TeV, by means of PYTHIA event generator. We introduced different geometrical setups. We have found strong proton-antiproton correlation, based on baryon number conservation and strong \( K^+-K^- \) correlation driven by strangeness conservation. Introducing different surrounding belts into the analysis further details were revealed. These correlations should be extracted from real data. The ALICE HMPID and the planned VHMPID detectors can play an important role in these explorations [9, 10].

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