PYTHIA Tune A, HERWIG, and JIMMY in Run 2 at CDF

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We study the behavior of the charged particle ($p_T > 0.5 \text{ GeV}/c$, $|\eta| < 1$) and energy ($|\eta| < 1$) components of the “underlying event” in hard scattering proton-antiproton collisions at 1.96 TeV. The goal is to produce data on the “underlying event” that is corrected to the particle level so that it can be used to tune the QCD Monte-Carlo models without requiring CDF detector simulation. Unlike the previous CDF Run 2 “underlying event” analysis which used JetClu to define “jets” and compared uncorrected data with the QCD Monte-Carlo models after detector simulation (i.e., CDFSIM), this analysis uses the MidPoint jet algorithm andcorrects the observables to the particle level. The corrected observables are then compared with the QCD Monte-Carlo models at the particle level (i.e., generator level). The QCD Monte-Carlo models include PYTHIA Tune A, HERWIG, and a tuned version of JIMMY.

One can use the topological structure of hadron-hadron collisions to study the “underlying event”. The direction of the leading calorimeter jet is used to isolate regions of $\eta$-$\phi$ space that are sensitive to the “underlying event”. As illustrated in Fig. 1, the direction of the leading jet, jet#1, is used to define correlations in the azimuthal angle, $\Delta \phi$. The angle $\Delta \phi = \phi - \phi_{\text{jet#1}}$ is the relative azimuthal angle between a charged particle (or a calorimeter tower) and the direction of jet#1. The “transverse” region is perpendicular to the plane of the hard 2-to-2 scattering and is therefore very sensitive to the “underlying event”. We restrict ourselves to charged particles in the range $p_T > 0.5 \text{ GeV}/c$ and $|\eta| < 1$ and calorimeter towers with $E_T > 0.1 \text{ GeV}$ and $|\eta| < 1$, but allow the leading jet that is used to define the “transverse” region to have $|\eta(\text{jet#1})| < 2$. Furthermore, we consider two classes of events. We refer to events in which there are no restrictions placed on the second and third highest $P_T$ jets (jet#2 and jet#3) as “leading jet” events. Events with at least two jets with $P_T > 15 \text{ GeV}/c$ where the leading two jets are nearly “back-to-back” ($|\Delta \phi| > 150^\circ$) with $P_T(\text{jet#2})/P_T(\text{jet#1}) > 0.8$ and $P_T(\text{jet#3}) < 15 \text{ GeV}/c$ are referred to as “back-to-back” events. “Back-to-back” events are a subset of the “leading jet” events. The idea is to suppress hard initial and final-state radiation thus increasing the sensitivity of the “transverse” region to the “beam-beam remnants” and the multiple parton scattering component of the “underlying event”.

As illustrated in Fig. 2, we define a variety of MAX and MIN “transverse” regions which helps separate the “hard component” (initial and final-state radiation) from the “beam-beam remnant” component. MAX (MIN) refer to the “transverse” region containing largest (smallest) number of charged particles or to the region containing the largest (smallest) scalar $P_T$ sum of charged particles or the region containing the largest (smallest) scalar $E_T$ sum of particles.

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FIG. 3: Data at 1.96 TeV on the density of charged particles, $dN_{\text{chg}}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the “transMAX” region (top) and the “transMIN” region (bottom) for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet $p_T$ compared with PYTHIA Tune A and HERWIG. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).

Since we will be studying regions in $\eta$-$\phi$ space with different areas, we will construct densities by dividing by the area. For example, the number density, $dN_{\text{chg}}/d\phi d\eta$, corresponds to the number of charged particles ($p_T > 0.5$ GeV/c) per unit $\eta$-$\phi$ and the PTsum density, $dPT_{\text{sum}}/d\phi d\eta$, corresponds to the amount of charged particle ($p_T > 0.5$ GeV/c) scalar PTsum per unit $\eta$-$\phi$, and the transverse energy density, $dET_{\text{sum}}/d\phi d\eta$, corresponds to the amount of scalar ETsum of all particles per unit $\eta$-$\phi$. One expects that “transMAX” region will pick up the hardest initial or final-state radiation while both the “transMAX” and “transMIN” regions should receive “beam-beam remnant” contributions. Hence one expects “transMIN” region to be more sensitive to the systematic uncertainty and compared with the theory at the particle level (i.e., generator level).
PYTHIA Tune A \cite{7,8,9,10,11} and HERWIG \cite{12,13} after detector simulation (i.e., CDFSIM). This analysis uses the MidPoint jet algorithm \((R = 0.7, \bar{f}_{\text{merge}} = 0.75)\) and corrects the observables to the particle level. The corrected observables are then compared with the QCD Monte-Carlo models at the particle level (i.e., generator level). The models includes PYTHIA Tune A, HERWIG, and a tuned version of JIMMY \cite{14}. In addition, for the first time we study the transverse energy density in the “transverse” region.

**Fig. 4:** Data at 1.96 TeV on scalar \(P_T\) sum density of charged particles, \(dP_T \text{sum} / d\phi d\eta\), with \(p_T > 0.5\) GeV/c and \(|\eta| < 1\) in the “transMAX” region (top) and the “transMIN” region (bottom) for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet \(P_T\) compared with PYTHIA Tune A and HERWIG. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).

**Fig. 5:** Data at 1.96 TeV on average transverse momentum, \(\langle p_T \rangle\), of charged particles with \(p_T > 0.5\) GeV/c and \(|\eta| < 1\) in the “transverse” region for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet \(P_T\) compared with PYTHIA Tune A and HERWIG. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).

Fig. 3 and Fig. 4 compare the data on the density of charged particles and the charged \(P_T\) sum density in the “transverse” region corrected to the particle level for “leading jet” and “back-to-back” events with PYTHIA Tune A and HERWIG at the particle level. As expected, the “leading jet” and “back-to-back” events behave quite differently. For the “leading jet” case the “transMAX” densities rise with increasing \(P_T\) (jet #1), while for the “back-to-back” case they fall with increasing \(P_T\) (jet #1). The rise in the “leading jet” case is, of course, due to hard initial and final-state radiation, which has been suppressed in the “back-to-back” events. The “back-to-back” events allow for a more close look at the “beam-beam remnant” and multiple parton scattering component of the “underlying event” and PYTHIA.
Tune A (with multiple parton interactions) does a better job describing the data than HERWIG (without multiple parton interactions).

The “transMIN” densities are more sensitive to the “beam-beam remnant” and multiple parton interaction component of the “underlying event”. The “back-to-back” data show a decrease in the “transMIN” densities with increasing $P_T$ (jet#1) which is described fairly well by PYTHIA Tune A (with multiple parton interactions) but not by HERWIG (without multiple parton interactions). The decrease of the “transMIN” densities with increasing $P_T$ (jet#1) for the “back-to-back” events is very interesting and might be due to a “saturation” of the multiple parton interactions at small impact parameter. Such an effect is included in PYTHIA Tune A but not in HERWIG (without multiple parton interactions).

Fig. 5 compares the data on average $p_T$ of charged particles in the “transverse” region corrected to the particle level for “leading jet” and “back-to-back” events with PYTHIA Tune A and HERWIG at the particle level. Again the “leading jet” and “back-to-back” events behave quite differently.

Fig. 6 shows the data corrected to the particle level for the scalar $ET$ sum density in the “transverse” region for “leading jet” and “back-to-back” events compared with PYTHIA Tune A and HERWIG. The scalar $ET$ sum density has been corrected to correspond to all particles (all $p_T$, $|\eta| < 1$). Neither PYTHIA Tune A nor HERWIG produce enough energy in the “transverse” region. HERWIG has more “soft” particles than PYTHIA Tune A and does slightly better in describing the energy density in the “transMAX” and “transMIN” regions.

Fig. 7 shows the difference of the “transMAX” and “transMIN” regions (“transDIF” = “transMAX” minus “transMIN”) for “leading jet” and “back-to-back” events compared with PYTHIA Tune A and HERWIG. “TransDIF” is more sensitive to the hard scattering component of the “underlying event” (i.e., initial and final state radiation). Both PYTHIA Tune A and HERWIG underestimate the energy density in the “transMAX” and “transMIN” regions (see Fig. 6). However, they both fit the “transDIF” energy density. This indicates that the excess energy density seen in the data probably arises from the “soft” component of the “underlying event” (i.e., beam-beam remnants and/or multiple parton interactions).

JIMMY is a model of multiple parton interaction which can be combined with HERWIG to enhance the “underlying event” thereby improving the agreement with data. Fig. 8 and Fig. 9 shows the energy density and charged $PT$ sum density, respectively, in the “transMAX” and “transMIN” regions for “leading jet” and “back-to-back” events compared with PYTHIA Tune A and a tuned version of JIMMY. JIMMY was tuned to fit the “transverse” energy density in “leading jet” events ($PT_{JIM} = 3.25$ GeV/c). The default JIMMY ($PT_{JIM} = 2.5$ GeV/c) produces too much energy and too much charged $PT$ sum in the “transverse” region. Tuned JIMMY does a good job of fitting

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**FIG. 6:** Data at 1.96 TeV on scalar $ET$ sum density, $dET_{sum}/d\phi d\eta$, for particles with $|\eta| < 1$ in the “transMAX” region (top) and the “transMIN” region (bottom) for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet $P_T$ compared with PYTHIA Tune A and HERWIG. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).
the energy and charged $PT$sum density in the “transverse” region (although it produces slightly too much charged $PT$sum at large $P_T$(jet#1)). However, the tuned JIMMY produces too many charged particles with $p_T > 0.5$ GeV/c (see Fig. 10). The particles produced by this tune of JIMMY are too soft. This can be seen clearly in Fig. 11 which shows the average charge particle $p_T$ in the “transverse” region.

The goal of this analysis is to produce data on the “underlying event” that is corrected to the particle level so that it can be used to tune the QCD Monte-Carlo models without requiring CDF detector simulation. Comparing the corrected observables with PYTHIA Tune A and HERWIG at the particle level (i.e., generator level) leads to the same conclusions as we found when comparing the uncorrected data with the Monte-Carlo models after detector simulation [6]. PYTHIA Tune A (with multiple parton interactions) does a better job in describing the “underlying event” (i.e., “transverse” regions) for both “leading jet” and “back-to-back” events than does HERWIG (without multiple parton interactions). HERWIG does not have enough activity in the “underlying event” for $P_T$(jet#1) less than about 150 GeV/c, which was also observed in our published Run 1 analysis [1].

This analysis gives our first look at the energy in the “underlying event” (i.e., the “transverse” region). Neither PYTHIA Tune A nor HERWIG produce enough transverse energy in the “transverse” region. However, they both fit the “transDIF” energy density (“transMAX” minus “transMIN”). This indicates that the excess energy density seen in the data probably arises from the “soft” component of the “underlying event” (i.e., beam-beam remnants and/or multiple parton interactions). HERWIG has more “soft” particles than PYTHIA Tune A and does slightly better in describing the energy density in the “transMAX” and “transMIN” regions. Tuned JIMMY does a good job of fitting the energy and charged $PT$sum density in the “transverse” region (although it produces slightly too much charged $PT$sum at large $P_T$(jet#1)). However, the tuned JIMMY produces too many charged particles with $p_T > 0.5$ GeV/c
FIG. 8: Data at 1.96 TeV on scalar $ET_{\text{sum}}$ density, $dET_{\text{sum}}/d\phi d\eta$, for particles with $|\eta| < 1$ in the “transMAX” region (top) and the “transMIN” region (bottom) for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet $P_T$ compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the “transverse” energy density in “leading jet” events ($P_T^{JIM} = 3.25$ GeV/c). The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).

FIG. 9: Data at 1.96 TeV on scalar $PT_{\text{sum}}$ density of charged particles, $dPT_{\text{sum}}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the “transMAX” region (top) and the “transMIN” region (bottom) for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet $P_T$ compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the “transverse” energy density in “leading jet” events ($P_T^{JIM} = 3.25$ GeV/c). The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).
FIG. 10: Data at 1.96 TeV on the density of charged particles, \( dN_{\text{chg}}/d\phi d\eta \), with \( p_T > 0.5 \text{ GeV}/c \) and |\( \eta \)| < 1 in the “transMAX” region (top) and the “transMIN” region (bottom) for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet \( P_T \) compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the “transverse” energy density in “leading jet” events (\( P_{T,JIM} = 3.25 \text{ GeV}/c \)). The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).

FIG. 11: Data at 1.96 TeV on average transverse momentum, \( \langle p_T \rangle \), of charged particles with \( p_T > 0.5 \text{ GeV}/c \) and |\( \eta \)| < 1 in the “transverse” region for “leading jet” and “back-to-back” events defined in Fig. 2 as a function of the leading jet \( P_T \) compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the “transverse” energy density in “leading jet” events (\( P_{T,JIM} = 3.25 \text{ GeV}/c \)). The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (i.e., generator level).

indicating that the particles produced by this tuned JIMMY are too soft.

In summary, we see interesting dependence of the “underlying event” on the transverse momentum of the leading jet (i.e., the \( Q^2 \) of the hard scattering). For the “leading jet” case the “transMAX” densities rise with increasing \( P_T \) (jet#1), while for the “back-to-back” case they fall with increasing \( P_T \) (jet#1). The rise in the “leading jet” case is due to hard initial and final-state radiation with \( p_T > 15 \text{ GeV}/c \), which has been suppressed in the “back-to-back” events. The “back-to-back” data show a decrease in the “transMIN” densities with increasing \( P_T \) (jet#1). The decrease of the “transMIN” densities with increasing \( P_T \) (jet#1) for the “back-to-back” events is very interesting and might be due to a “saturation” of the multiple parton interactions at small impact parameter. Such an effect is included in PYTHIA Tune A (with multiple parton interactions) but not in HERWIG (without multiple parton interactions). PYTHIA Tune A does predict this decrease, while HERWIG shows an increase (due to increasing initial and final
state radiation).

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