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

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We study the behavior of the charged particle ($p_T > 0.5\,\mathrm{GeV/c}$, $|\eta| < 1$) 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 and corrects the observables to the particle level. The corrected observables are then compared with the QCD Monde-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" [1–3]. The direction of the leading calorimeter jet is used to isolate regions of η-ϕ 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 $\Delta\phi = \phi - \phi_{\mathrm{jet}\#1}$ 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 $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ and calorimeter towers with $E_T > 0.1\,\mathrm{GeV}$ and $|\eta| < 1$, but allow the leading jet that is used to define the "transverse" region to have $|\eta(jet\#1)| < 2$. 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 $P_T > 15\,\mathrm{GeV/c}$ where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150^\circ$) with $P_T(jet\#2)/P_T(jet\#1) > 0.8$ and $P_T(jet\#3) < 15\,\mathrm{GeV/c}$ 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".

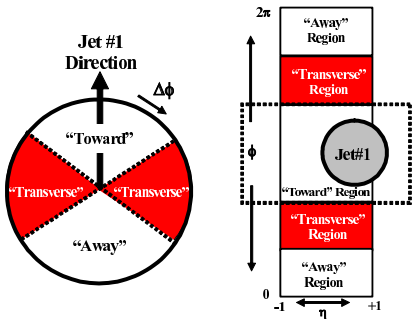

FIG. 1: Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (MidPoint, $R = 0.7$, $f_{merge} = 0.75$) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\mathrm{jet1}}$ is the relative azimuthal angle between charged particles and the direction of jet#1. The "transverse" region is defined by $60^\circ < |\Delta\phi| < 120^\circ$ and $|\eta| < 1$. We examine charged particles in the range $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ and calorimeter towers with $|\eta| < 1$, but allow the leading jet to be in the region $|\eta(\mathrm{jet}\#1)| < 2$.

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 PTsum of charged particles or the region containing the largest (smallest) scalar ETsum of particles.

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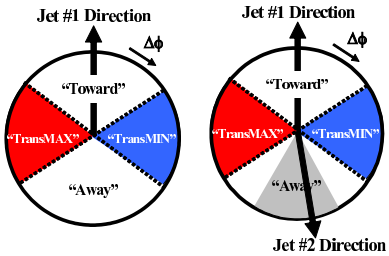

FIG. 2: Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (highest P_T jet) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\rm jet\#1}$ is the relative azimuthal angle between charged particles and the direction of jet#1. On an event by event basis, we define "transMAX" ("transMIN") to be the maximum (minimum) of the two "transverse" regions, $60^\circ < \Delta\phi < 120^\circ$ and $60^\circ < -\Delta\phi < 120^\circ$. "transMAX" and "transMIN" each have an area in η-ϕ space of $\Delta\eta\Delta\phi = 4\pi/6$. The overall "transverse" region defined in Fig. 1 contains both the "transMAX" and the "transMIN" regions. Events in which there are no restrictions placed on the second and third highest P_T jets (jet#2 and jet#3) are referred to as "leading jet" events (*left*). Events with at least two jets with $P_T > 15\,{\rm GeV/c}$ where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150^\circ$) with $P_T({\rm jet\#2})/P_T({\rm jet\#1}) > 0.8$ and $P_T({\rm jet\#3}) < 15\,{\rm GeV/c}$ are referred to as "back-to-back" events (*right*).

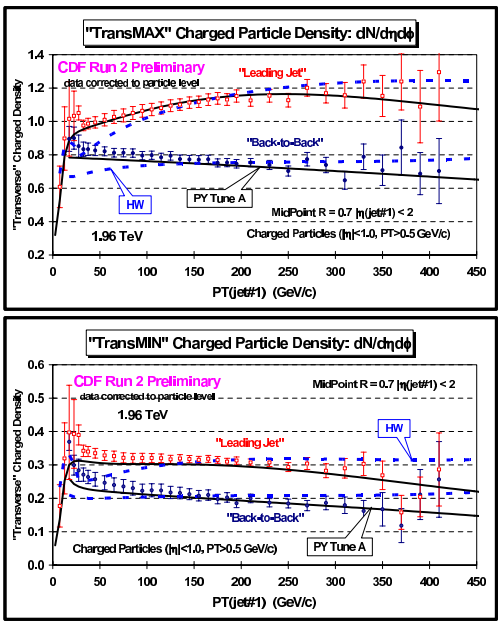

FIG. 3: Data at 1.96 TeV on the density of charged particles, $dN_{chg}/d\phi d\eta$ with $p_T > 0.5\,{\rm GeV/c}$ and $|\eta| < 1$ in the "transMAX" region (*top*) and the "transMIN" region (*bottom*) for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T 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 η-ϕ space with different areas, we will construct densities by dividing by the area. For example, the number density, $dN_{chg}/d\phi d\eta$, corresponds the number of charged particles ($p_T > 0.5\,{\rm GeV/c}$) per unit η-ϕ and the PTsum density, $dPT_{sum}/d\phi d\eta$, corresponds the amount of charged particle ($p_T > 0.5\,{\rm GeV/c}$) scalar PTsum per unit η-ϕ, and the transverse energy density, $dET_{sum}/d\phi d\eta$, corresponds the amount of scalar ETsum of all particles per unit η-ϕ. 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 "beam-beam remnant" component of the "underlying event", while the "transMAX" minus the "transMIN" (*i.e.*, "transDIF") is very sensitive to hard initial and final-state radiation. This idea, was first suggested by Bryan Webber, and implemented by in a paper by Jon Pumplin [4]. Also, Valaria Tano studied this in her CDF Run 1 analysis of maximum and minimum transverse cones [5].

Our previous Run 2 "underlying event" analysis [6] used JetClu to define "jets and compared uncorrected data

with PYTHIA Tune A [7–11] and HERWIG [12, 13] after detector simulation (*i.e.*, CDFSIM). This analysis uses the MidPoint jet algorithm ($R = 0.7$, $f_{merge} = 0.75$) 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 [14]. In addition, for the first time we study the transverse energy density in the "transverse" region.

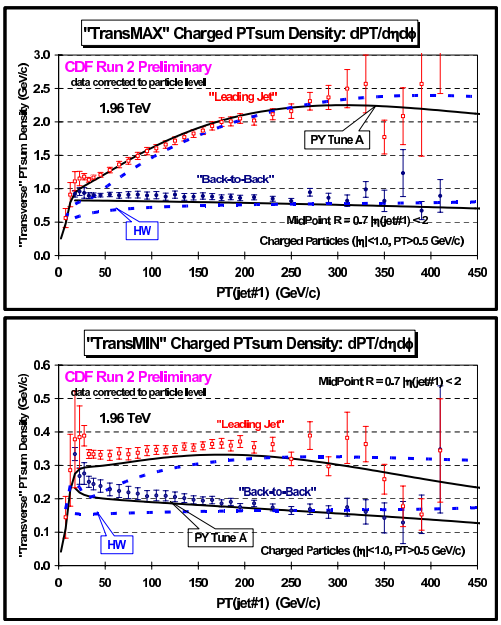

FIG. 4: Data at 1.96 TeV on scalar PTsum density of charged particles, $dPT_{sum}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" region (*top*) and the "transMIN" region (*bottom*) for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet 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).

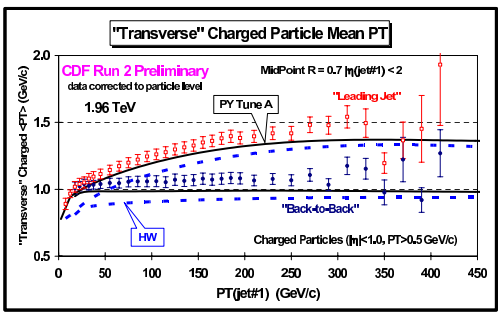

FIG. 5: Data at 1.96 TeV on average transverse momentum, $\langle p_T \rangle$, of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune A and HERWIG. 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 PTsum 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

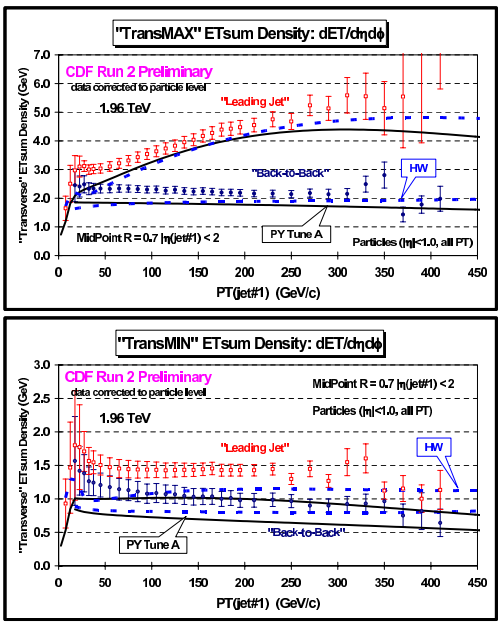

FIG. 6: Data at 1.96 TeV on scalar ETsum density, $dET_{sum}/d\phi d\eta$, for particles with $|\eta| < 1$ in the "transMAX" region (*top*) and the "transMIN" region (*bottom*) for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune 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).

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 ETsum density in the "transverse" region for "leading jet" and "back-to-back" events compared with PYTHIA Tune A and HERWIG. The scalar ETsum density has been corrected to correcpond 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 PTsum 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 ($PTJIM = 3.25\,\mathrm{GeV/c}$). The default JIMMY ($PTJIM = 2.5\,\mathrm{GeV/c}$) produces too much energy and too much charged PTsum in the "transverse" region. Tuned JIMMY does a good job of fitting

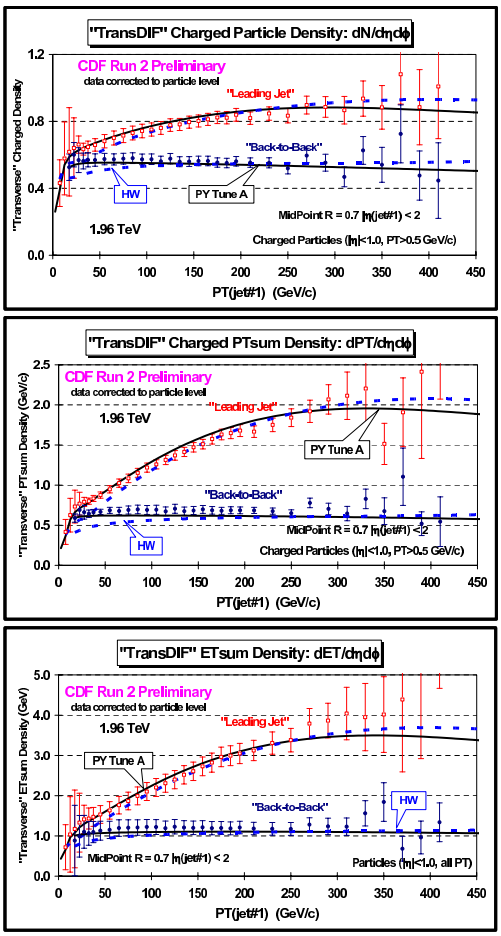

FIG. 7: Data at 1.96 TeV on the difference of the "transMAX" and "transMIN" regions ("transDIF" = "transMAX"- "transMIN") for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune A and HERWIG. The data are corrected to the particle level (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 PTsum density in the "transverse" region (although it produces slightly too much charged PTsum 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 PTsum density in the "transverse" region (although it produces slightly too much charged PTsum at large P_T(jet#1)). However, the tuned JIMMY produces too many charged particles with $p_T > 0.5$ GeV/c

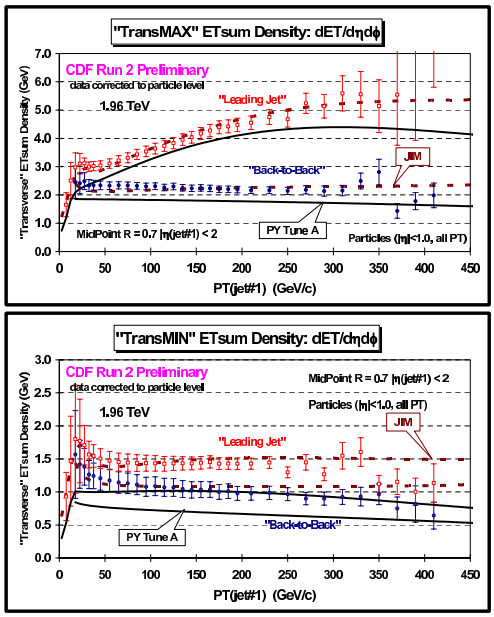

FIG. 8: Data at 1.96 TeV on scalar ETsum density, $dET_{sum}/d\phi d\eta$, for particles with $|\eta| < 1$ in the "transMAX" region (*top*) and the "transMIN" region (*bottom*) for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the "transverse" energy density in "leading jet" events ($PTJIM = 3.25\,\mathrm{GeV/c}$). 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).

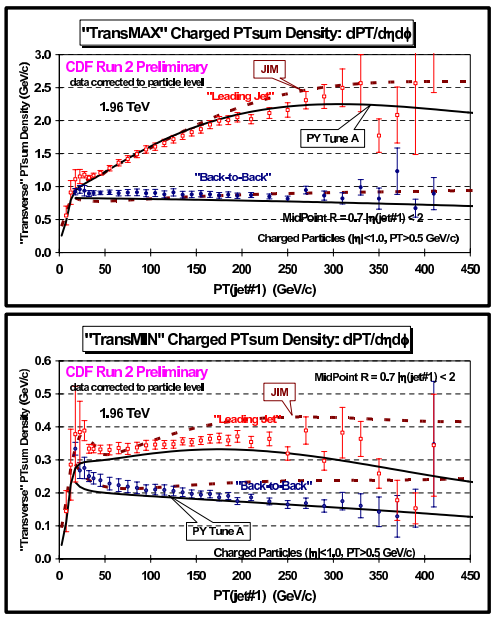

FIG. 9: Data at 1.96 TeV on scalar PTsum density of charged particles, $dPT_{sum}/d\phi d\eta$, with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ in the "transMAX" region (*top*) and the "transMIN" region (*bottom*) for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the "transverse" energy density in "leading jet" events ($PTJIM = 3.25\,\mathrm{GeV/c}$). 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).

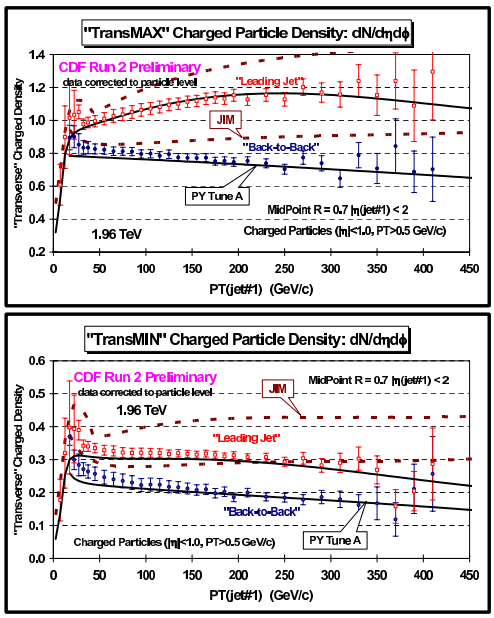

FIG. 10: Data at 1.96 TeV on the density of charged particles, $dN_{chg}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" region (*top*) and the "transMIN" region (*bottom*) for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the "transverse" energy density in "leading jet" events ($PTJIM = 3.25$ 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).

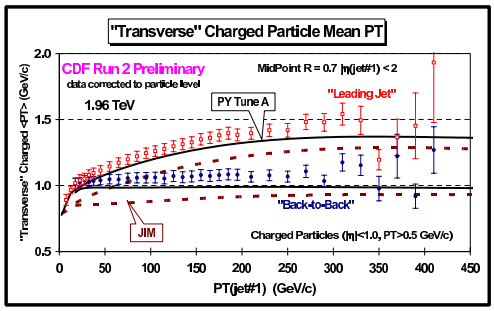

FIG. 11: Data at 1.96 TeV on average transverse momentum, $\langle p_T \rangle$, of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" and "back-to-back" events defined in Fig. 2 as a function of the leading jet P_T compared with PYTHIA Tune A and tuned JIMMY. JIMMY was tuned to fit the "transverse" energy density in "leading jet" events ($PTJIM = 3.25$ 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).

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 $p_T > 15$ 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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