CDF/PUB/JET/PUBLIC/6821

Using Correlations in the Transverse Region to Study the Underlying Event in Run 2 at the Tevatron*

Alberto Cruz[1] and Rick Field[1]

[1] *Department of Physics, University of Florida, Gainesville, Florida, 32611, USA*

(Dated: January 4, 2004)

We study the behavior of the charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) component of the "underlying event" in hard proton-antiproton collisions at 1.96 TeV and compare with PYTHIA Tune A and HERWIG. We use the direction of the leading calorimeter jet in each event to define two "transverse" regions of η-ϕ space that are very sensitive to the "underlying event". Comparing these two "transverse" regions on an event-by-event basis provides a more detailed look at the "underlying event". In addition, selecting events with at least two jets that are nearly "back-to-back" ($|\Delta\phi| > 150°$) allows for a more detailed study of the "beam-beam remnants" and multiple parton scattering component of the "underlying event". The average p_T versus the number of charged particles in the "transverse" region is compared with "min-bias" collisions. In addition, we study the number and $\langle p_T \rangle$ of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region. PYTHIA Tune A (with multiple parton interactions) does a better job in describing the detailed properties of the "underlying event" than HERWIG (without multiple parton interactions).

I. INTRODUCTION

Fig. 1 illustrates the way QCD Monte-Carlo models simulate a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, p_T(hard), has occurred. The resulting event contains particles that originate from the two outgoing partons (plus initial and final-state radiation) and particles that come from the breakup of the proton and antiproton (*i.e.*, "beam-beam remnants"). The "underlying event" is everything except the two outgoing hard scattered "jets" and receives contributions from the "beam-beam remnants" plus initial and final-state radiation. The "hard scattering" component consists of the outgoing two jets plus initial and final-state radiation.

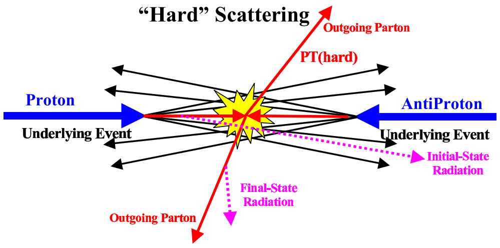

FIG. 1: Illustration of the way QCD Monte-Carlo models simulate a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, p_T(hard), has occurred. The resulting event contains particles that originate from the two outgoing partons (plus initial and final-state radiation) and particles that come from the breakup of the proton and antiproton (*i.e.*, "beam-beam remnants"). The "underlying event" is everything except the two outgoing hard scattered "jets" and consists of the "beam-beam remnants" plus initial and final-state radiation. The "hard scattering" component consists of the outgoing two jets plus initial and final-state radiation.

The "beam-beam remnants" are what is left over after a parton is knocked out of each of the initial two beam hadrons. It is the reason hadron-hadron collisions are more "messy" than electron-positron annihilations and no one really knows how it should be modeled. For the QCD Monte-Carlo models the "beam-beam remnants" are an important component of the "underlying event". Also, it is possible that multiple parton scattering contributes to the "underlying event". Fig. 2 shows the way PYTHIA [1] models the "underlying event" in proton-antiproton collisions by including multiple parton interactions. In addition to the hard 2-to-2 parton-parton scattering and the "beam-beam remnants", sometimes there is a second "semi-hard" 2-to-2 parton-parton scattering that contributes particles to the "underlying event".

* Contribution to the QCD/SM Group at Les Houches 2003.

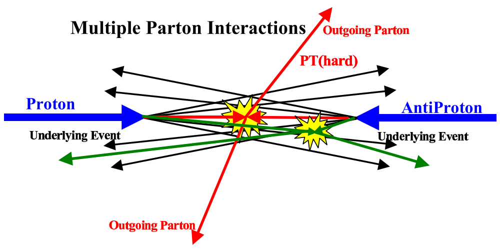

FIG. 2: Illustration of the way PYTHIA models the "underlying event" in proton-antiproton collisions by including multiple parton interactions. In addition to the hard 2-to-2 parton-parton scattering with transverse momentum, p_T(hard), there is a second "semi-hard" 2-to-2 parton-parton scattering that contributes particles to the "underlying event".

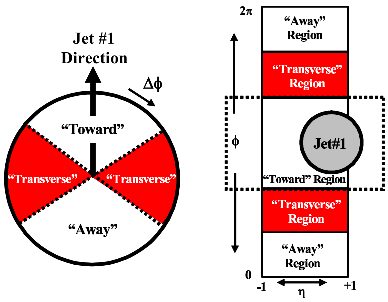

FIG. 3: Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (JetClu, $R = 0.7$) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\rm jet1}$ is the relative azimuthal angle between charged particles and the direction of jet# 1. The "toward" region is defined by $|\Delta\phi| < 60°$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120°$ and $|\eta| < 1$. The "transverse" region is defined by $60° < |\Delta\phi| < 120°$ and $|\eta| < 1$. Each of the three regions "toward", "transverse", and "away" have an area in η-ϕspace of $\Delta\eta\Delta\phi = 4\pi/3$. We examine charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$, but allow the leading jet to be in the region $|\eta(\text{jet}\#1)| < 2$.

Of course, from a certain point of view there is no such thing as an "underlying event" in a proton-antiproton collision. There is only an "event" and one cannot say where a given particle in the event originated. On the other hand, hard scattering collider "jet" events have a distinct topology. On the average, the outgoing hadrons "remember" the underlying the 2-to-2 hard scattering subprocess. An average hard scattering event consists of a collection (or burst) of hadrons traveling roughly in the direction of the initial beam particles and two collections of hadrons (*i.e.*, "jets") with large transverse momentum. The two large transverse momentum "jets" are roughly "back-to-back" in

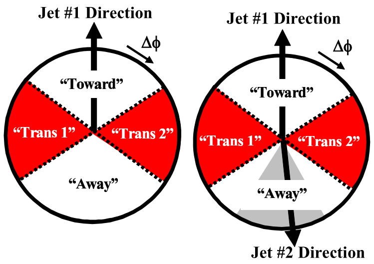

FIG. 4: Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (highest E_T jet) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\rm jet1}$ is the relative azimuthal angle between charged particles and the direction of jet#1. The two "transverse" regions $60° < \Delta\phi < 120°$ and $60° < -\Delta\phi < 120°$ are referred to as "transverse 1" and "transverse 2". Each of the two "transverse" regions have an area in η-ϕ space of $\Delta\eta\Delta\phi = 4\pi/6$. The overall "transverse" region defined in Fig. 3 corresponds to combining the "transverse 1" and "transverse 2" regions. Events in which there are no restrictions placed on the on the second highest E_T jet, jet#2, are referred to as "leading jet" events (*left*). Events with at least two jets with $|\eta(\text{jet})| < 2$, where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150°$) with $E_T(jet\#2)/E_T(jet\#1) > 0.8$ are referred to as "back-to-back" events. (*right*).

azimuthal angle. One can use the topological structure of hadron-hadron collisions to study the "underlying event" [2–5]. Here we study the "underlying event" in the Run 2 using the direction of the leading calorimeter jet (JetClu, $R = 0.7$) to isolate regions of η-ϕ space that are sensitive to the "underlying event".

As illustrated in Fig. 3, the direction of the leading jet, jet# 1, is used to define correlations in the azimuthal angle, ϕ. The angle $\Delta\phi = \phi - \phi_{\rm jet1}$ is the relative azimuthal angle between a charged particle and the direction of jet# 1. The "toward" region is defined by $|\Delta\phi| < 60°$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120°$ and $|\eta| < 1$. The "transverse" region is defined by $60° < |\Delta\phi| < 120°$ and $|\eta| < 1$. The three regions "toward", "transverse", and "away" are shown in Fig. 3. Each region has an area in η-ϕspace of $\Delta\eta\Delta\phi = 4\pi/3$. 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 $p_T > 0.5$ GeV/c and $|\eta| < 1$, but allow the leading jet that is used to define the "transverse" region to have $|\eta(\text{jet}\#1)| < 2$.

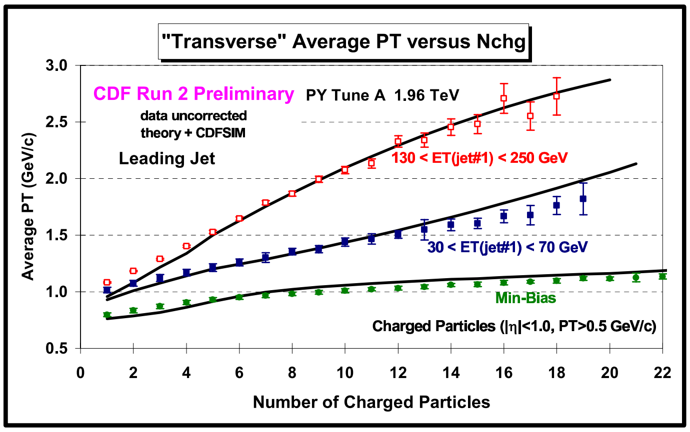

FIG. 5: Run 2 data on the average transverse momentum as a function number of particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events defined in Fig. 4 with $30 < E_T(\text{jet}\#1) < 70$ GeV and $130 < E_T(\text{jet}\#1) < 250$ GeV. Also shown are the data on the average transverse momentum as a function of the number particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "min-bias" collisions at 1.96 TeV. The theory curves correspond to PYTHIA Tune A at 1.96 TeV (after CDFSIM).

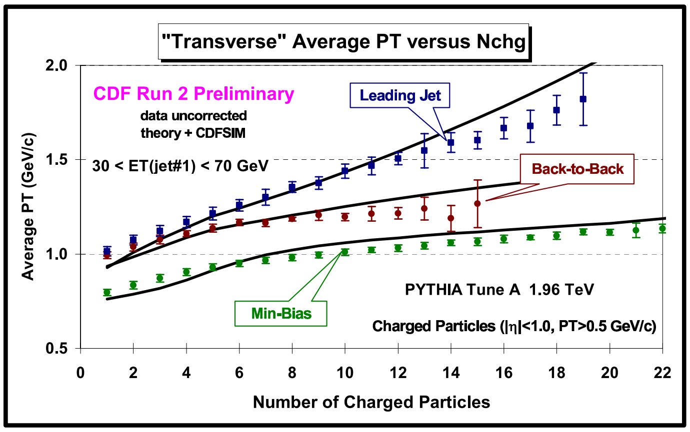

FIG. 6: Run 2 data on the average transverse momentum as a function of the number of particles for particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events and for "back-to-back" events defined in Fig. 4 with $30 < E_T(\text{jet}\#1) < 70$ GeV. Also shown are the data on the average transverse momentum as a function of the number particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "min-bias" collisions at 1.96 TeV. The theory curves correspond to PYTHIA Tune A at 1.96 TeV (after CDFSIM).

In this analysis we look in more detail at the two "transverse" regions defined in Fig. 4. The overall "transverse" region in Fig. 3 corresponds to combining the "transverse 1" and "transverse 2" regions. Comparing these two "transverse" regions on an event-by-event basis provides a closer look at the "underlying event". Here we refer to

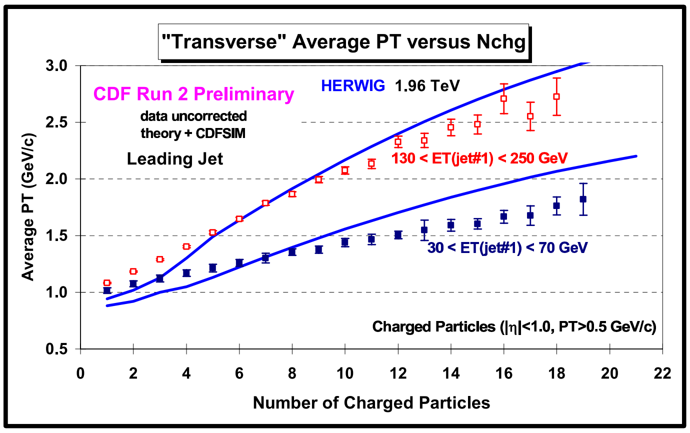

FIG. 7: Run 2 data on the average transverse momentum as a function of the number of particles for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ in the "transverse" region for "leading jet" events defined in Fig. 4 with $30 < E_T(\mathrm{jet\#1}) < 70\,\mathrm{GeV}$ and $130 < E_T(\mathrm{jet\#1}) < 250\,\mathrm{GeV}$ compared to HERWIG at 1.96 TeV (after CDFSIM).

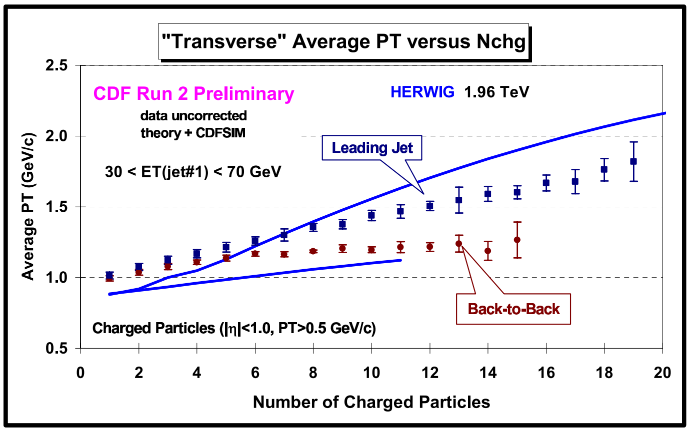

FIG. 8: Run 2 data on the average transverse momentum as a function of the number of particles for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ in the "transverse" region for "leading jet" and "back-to-back" events defined in Fig. 4 with $30 < E_T(\mathrm{jet\#1}) < 70\,\mathrm{GeV}$ compared to HERWIG at 1.96 TeV (after CDFSIM).

events in which there are no restrictions placed on the second highest E_T jet, jet#2, as "leading jet" events. Our previous analysis of the "underlying event" we only considered "leading jet" events [2, 4, 5]. In this analysis we define a second class of events. Events with at least two jets with $|\eta(\mathrm{jet})| < 2$, where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150°$) with $E_T(jet\#2)/E_T(jet\#1) > 0.8$ are referred to as "back-to-back" events. "Back-to-back" events are a subset of the "leading jet" events. The idea here 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 in our published Run 1 analysis [2] we consider charged particles only in the region $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ where the COT efficiency is high and compare uncorrected data with PYTHIA Tune A [4] and HERWIG [6] after detector corrections (*i.e.*, CDFSIM). Systematic errors are calculated in the same way as in our Run 1 analysis. We generate every plot twice, once with our chosen track selection cuts and again with the very tight track cuts. The change in each point in every plot due to this tighter cut is used as a measure of the systematic error and is added in quadrature with the statistical error to form the overall error.

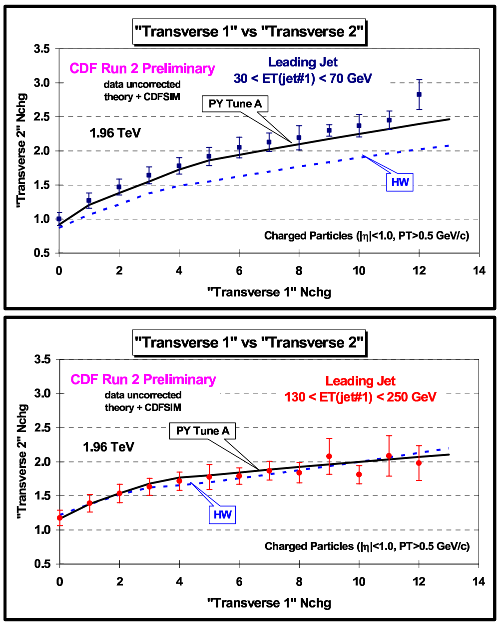

FIG. 9: Run 2 data on the average number of particles in the "transverse 2" region defined in Fig. 4 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ for "leading jet" events with $30 < E_T(\text{jet}\#1) < 70\,\mathrm{GeV}$ (*top*) and $130 < E_T(\text{jet}\#1) < 250\,\mathrm{GeV}$ (*bottom*). The theory curves correspond to PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

II. TRANSVERSE AVERAGE P_T VERSUS N_{CHG}

A. Definition

We study the average transverse momentum of charged particles in the "transverse" region as a function of the number of charged particles in the "transverse" region for $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$. The average transverse momentum, $\langle p_T \rangle$, is formed, on an event-by-event basis, and then plotted as a function of the charged multiplicity. The idea here is to look for correlations between multiplicity and $\langle p_T \rangle$. If, for example, there is a mixture of "hard" and "soft" events then one expects that $\langle p_T \rangle$ will increase with multiplicity because demanding a large multiplicity will preferentially select the "hard" process that also has a larger $\langle p_T \rangle$. On the other hand, it may be possible to get a high multiplicity in a "soft" collision so the rate that $\langle p_T \rangle$ rises with multiplicity is a rough measure of the "hard" and "soft" mixture. The steeper the slope the larger the "hard" component. There is a very nice published CDF Run 1 analysis that looks at this in "min-bias" collisions [7], but it has never previously been studied in the "transverse" region of a "hard" scattering process.

B. Overall Transverse Region

Fig. 5 shows uncorrected Run 2 data on the $\langle p_T \rangle$ of charged particles versus the number of charged particles in min-bias collisions and in the "transverse" region for "leading jet" events with $30 < E_T(\text{jet}\#1) < 70\,\mathrm{GeV}$ and $130 < E_T(\text{jet}\#1) < 250\,\mathrm{GeV}$ compared with PYTHIA Tune A (after CDFSIM). The data suggest that there is more "hard" scattering in the "transverse" region (*i.e.*, initial and final-state radiation) than there is in an average "min-bias" collision.

Fig. 6 shows the $\langle p_T \rangle$ of charged particles versus the number of charged particles in "min-bias" collisions and in the "transverse" region for "leading jet" and "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70\,\mathrm{GeV}$ compared with PYTHIA Tune A (after CDFSIM). The "transverse" region for the "back-to-back" events looks more like an average "min-bias" collision, which is exactly what one expects since the "back-to-back" requirement suppress hard initial and final-state radiation.

Fig. 7 compares HERWIG (after CDFSIM) with the data on the $\langle p_T \rangle$ of charged particles in the "transverse" region versus the number of charged particles in the "transverse" region for "leading jet" events with $30 < E_T(\text{jet}\#1) <$

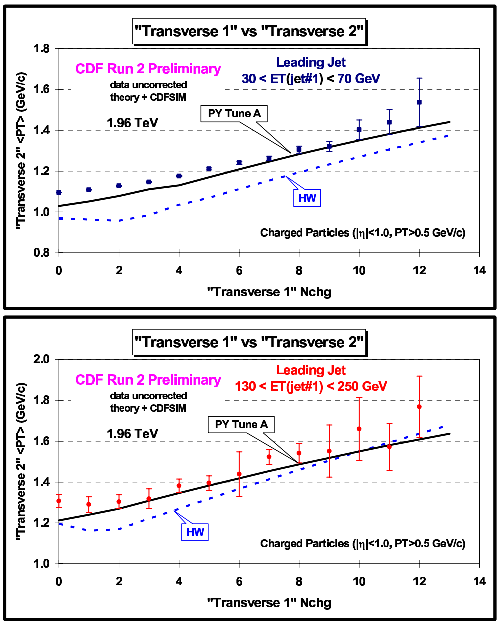

FIG. 10: Run 2 data on the average transverse momentum of particles in the "transverse 2" region defined in Fig. 4 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events with $30 < E_T(\text{jet}\#1) < 70$ GeV (*top*) and $130 < E_T(\text{jet}\#1) < 250$ GeV (*bottom*). The theory curves correspond to PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

70 GeV and $130 < E_T(\text{jet}\#1) < 250$ GeV.

Fig. 8 compares HERWIG (after CDFSIM) with the data on the $\langle p_T \rangle$ of charged particles in the "transverse" region versus the number of charged particles in the "transverse" region for "leading jet" and "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV. HERWIG (without multiple parton interactions) does not describe the data as well as PYTHIA Tune A (with multiple parton interactions).

C. Transverse 1 verses transverse 2

Fig. 9 shows the number of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region for "leading jet" events with $30 < E_T(\text{jet}\#1) < 70$ GeV and $130 < E_T(\text{jet}\#1) < 250$ GeV compared with PYTHIA Tune A and HERWIG after CDFSIM.

Fig. 10 shows the $\langle p_T \rangle$ of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region for "leading jet" events with $30 < E_T(\text{jet}\#1) < 70$ GeV and $130 < E_T(\text{jet}\#1) < 250$ GeV compared with PYTHIA Tune A and HERWIG after CDFSIM.

Fig. 11 shows the number and $\langle p_T \rangle$ of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region for "leading jet" and "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV compared with PYTHIA Tune A (after CDFSIM).

Fig. 12 shows the number and $\langle p_T \rangle$ of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region for "leading jet" and "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV compared with HERWIG (after CDFSIM). HERWIG (without multiple parton interactions) does not do nearly as well describing the "transverse 2" versus "transverse 1" correlations seen in the data as does PYTHIA Tune A (with multiple parton interactions).

III. SUMMARY

This analysis takes a closer look at the "underlying event" in hard scattering proton-antiproton collisions at 1.96 TeV. We look only at the charged particle component of the "underlying event" and restrict the charged particles to be in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$. We use the direction of the leading calorimeter jet in each event to define two "transverse" regions of η-ϕ space that are very sensitive to the "underlying event". Comparing these two "transverse"

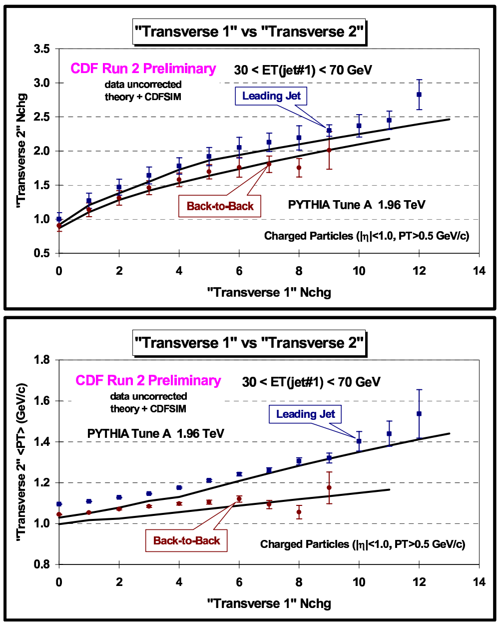

FIG. 11: Run 2 data on the average number of particles (*top*) and the average transverse momentum of particles (*bottom*) in the "transverse 2" region defined in Fig. 4 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events and "back-to-back" events with $30 < E_T(\mathrm{jet}\#1) < 70$ GeV. The theory curves correspond to PYTHIA Tune A at 1.96 TeV (after CDFSIM).

regions on an event-by-event basis provides more details about the "underlying event". In addition, by selecting events with at least two jets that are nearly "back-to-back" ($|\Delta\phi| > 150°$) we are able to look closer at the "beam-beam remnants" and multiple parton interaction components of the "underlying event". PYTHIA Tune A (with multiple parton interactions) does a good job in describing the "underlying event" (*i.e.*, "transverse" regions) for both "leading jet" and "back-to-back" events. HERWIG (without multiple parton interactions) does not have enough activity in the "underlying event", which was also observed in our published Run 1 analysis [2].

The data presented here show interesting correlations between the two "transverse" regions defined in Fig. 4. The charged multiplicity and the $\langle p_T \rangle$ in the "transverse 2" region increases with the charged multiplicity in the "transverse 1" region. This is a new type of correlation. It might simply be due to a high multiplicity in "transverse 1" biasing in favor of a harder 2-to-2 scattering (*i.e.*, higher p_T(hard)) which would result in a higher multiplicity and larger $\langle p_T \rangle$ in "transverse 2". However, we have seen in previous studies [2–5] that the average charged particle density in the "transverse" region does not change much as one increases E_T(jet#1). It is possible that the "transverse 1" versus "transverse 2" correlations arise from multiple parton interactions. A large multiplicity in the "transverse 1" region would indicate a small impact parameter collision has occurred with several multiple parton scatterings which would then cause an increased multiplicity and $\langle p_T \rangle$ in the "transverse 2" region. The fact that PYTHIA Tune A (with multiple parton interactions) agrees with the data better than HERWIG (without multiple parton interactions) is very interesting. However, much more work is necessary to actually pinpoint the source of the "transverse 1" versus "transverse 2" correlations.

[1] T. Sjostrand, Phys. Lett. **157B**, 321 (1985); M. Bengtsson, T. Sjostrand, and M. van Zijl, Z. Phys. **C32**, 67 (1986); T. Sjostrand and M. van Zijl, Phys. Rev. **D36**, 2019 (1987).

[2] *Charged Jet Evolution and the Underlying Event in Proton-Antiproton Collisions at* 1.8 *TeV*, The CDF Collaboration (T. Affolder et al.), Phys. Rev. **D65**, 092002, (2002).

[3] *A Comparison of the Underlying Event in Jet and Min-Bias Events*, talk presented by Joey Huston at DPF2000, Columbus, OH, August 11, 2000. *The Underlying Event in Jet and Minimum Bias Events at the Tevatron*, talk presented by Valeria Tano at ISMD2001, Datong, China, September 1–7, 2001.

[4] *Min-Bias and the Underlying Event at the Tevatron and the LHC*, talk presented by R. Field at the Fermilab ME/MC Tuning Workshop, Fermilab, October 4, 2002. *Toward an Understanding of Hadron Collisions: From Feynman-Field until*

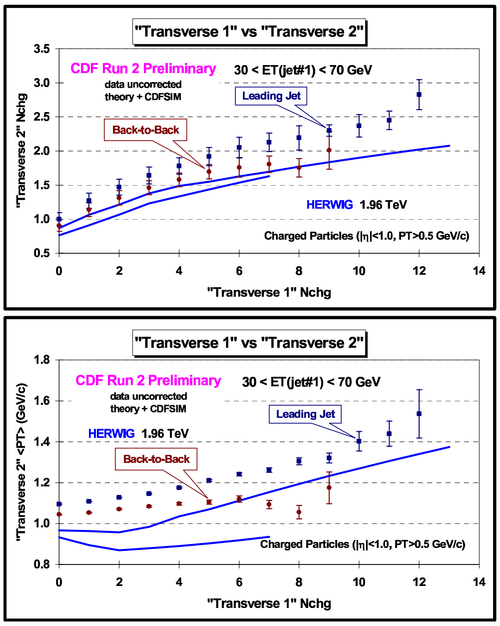

FIG. 12: Run 2 data on the average number of particles (*top*) and the average transverse momentum of particles (*bottom*) in the "transverse 2" region defined in Fig. 4 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events and "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV. The theory curves correspond to HERWIG at 1.96 TeV (after CDFSIM).

Now, talk presented by R. Field at the Fermilab Joint Theoretical Experimental "Wine & Cheese" Seminar, Fermilab, October 4, 2002.

[5] *Min-Bias and the Underlying Event at CDF*, talk presented by R. Field at the Monte-Carlo Tools for the LHC Workshop, CERN, July 31, 2003.

[6] G. Marchesini and B. R. Webber, Nucl. Phys **B310**, 461 (1988); I. G. Knowles, Nucl. Phys. **B310**, 571 (1988); S. Catani, G. Marchesini, and B. R. Webber, Nucl. Phys. **B349**, 635 (1991).

[7] *Soft and Hard Interactions in Proton-AntiProton Collisions at* 1800 *and* 630 *GeV*, The CDF Collaboration (D. Acosta et al.), Phys. Rev. **D65**, 07200, (2002).