Min-Bias and the Underlying Event in Run 2 at CDF

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We study the topology of "min-bias" and hard collisions in Run 2 at the Tevatron by examining charged particle correlations. The $\Delta\phi$ dependence of the density of charged particles and the scalar p_T sum density relative to the direction of the leading jet for "leading jet" and "back-to-back" events are studied. We refer to events in which there are no restrictions placed on the second and third highest E_T jets (jet#1 and jet#2) as "leading jet" events. Events with at least two jets with $E_T > 15\,\mathrm{GeV}$ where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150°$) with $E_T(\text{jet\#2})/E_T(\text{jet\#1}) > 0.8$ and $E_T(\text{jet\#3}) < 15\,\mathrm{GeV}$ are referred to as "back-to-back" events. Selecting "back-to-back" events suppresses hard initial and final-state radiation thus increasing the sensitivity of the "transverse" region to the "beam-beam remnants" and the multiple parton scattering components of the "underlying event". To examine the jet structure in the "underlying event" we define "associated" charged particle densities that measure the number of charged particles and scalar p_T sum of charged particles accompanying the maximum p_T charged particle in the "transverse" region, $PT\max T$. The jet structure in "min-bias" collisions is studied by defining "associated" charged particle densities relative to the direction of the maximum p_T particle in the event, $PT\max$. 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).

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.

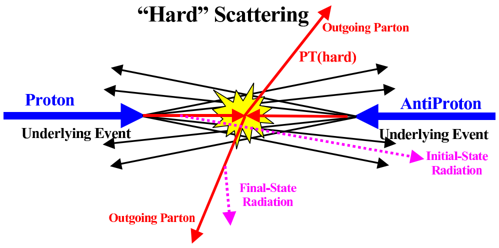

FIG. 1: Illustration of the way QCD Monte-Carlo models simulate a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, p_T(hard), has occurred. The resulting event contains particles that originate from the two outgoing partons (plus initial and final-state 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 collision by including multiple parton interactions. In addition to the hard 2-to-2 parton-parton scattering and the "beam-beam

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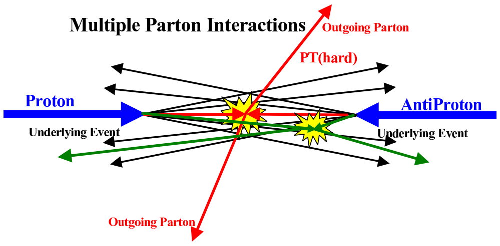

FIG. 2: Illustration of the way PYTHIA models the "underlying event" in proton-antiproton collisions by including multiple parton interactions. In addition to the hard 2-to-2 parton-parton scattering with transverse momentum, p_T(hard), there is a second "semi-hard" 2-to-2 parton-parton scattering that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

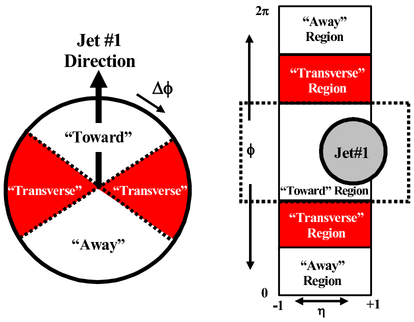

FIG. 3: Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (JetClu, $R = 0.7$) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\rm jet1}$ is the relative azimuthal angle between charged particles and the direction of jet#1. The "toward" region is defined by $|\Delta\phi| < 60^\circ$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120^\circ$ and $|\eta| < 1$. The "transverse" region is defined by $60^\circ < |\Delta\phi| < 120^\circ$ and $|\eta| < 1$. Each of the three regions "toward", "transverse", and "away" have an area in η-ϕ space 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 $|\eta(\text{jet\#1})| < 2$.

remnants", sometimes there is a second "semi-hard" 2-to-2 parton-parton scattering that contributes particles to the "underlying event".

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 2-to-2 hard scattering subprocess. An average hard scattering event consists of a collection (or burst)

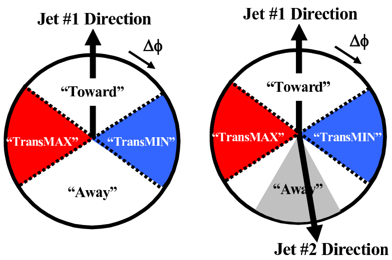

FIG. 4: Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (highest E_T jet) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\rm jet1}$ is the relative azimuthal angle between charged particles and the direction of jet#1. On an event by event basis, 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. 3 contains both the "transMAX" and the "transMIN" regions. Events in which there are no restrictions placed on the second and third highest E_T jets (jet#2 and jet#3) are referred to as "leading jet" events (*left*). Events with at least two jets with $E_T > 15$ GeV where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150^\circ$) with $E_T(\text{jet\#2})/E_T(\text{jet\#1}) > 0.8$ and $E_T(\text{jet\#3}) < 15$ GeV are referred to as "back-to-back" events (*right*).

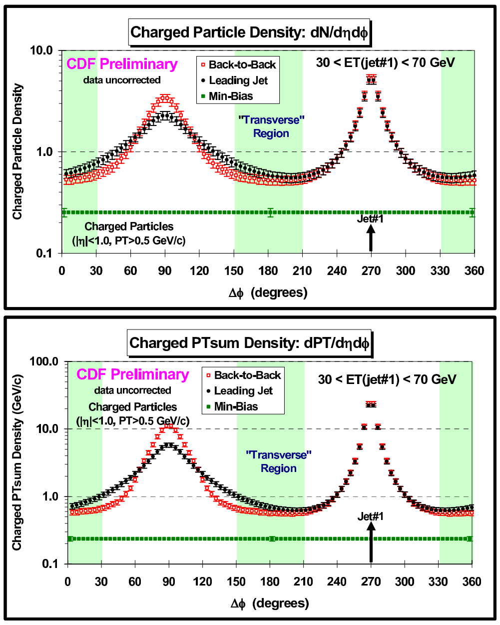

FIG. 5: Run 2 data on the $\Delta\phi$ dependence of the density of charged particles, $dN_{chg}/d\phi d\eta$ (*top*), and the scalar PTsum density, $dPT_{sum}/d\phi d\eta$ (*bottom*), for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to the direction of the leading jet for $30 < E_T(\text{jet}\#1) < 70$ GeV (rotated to 270°) for "leading jet" and "back-to-back" events as defined in Fig. 4. Also shown is the average density of charged particles, $dN_{chg}/d\phi d\eta$ (*top*) and the scalar PTsum density, $dPT_{sum}/d\phi d\eta$ (*bottom*) for "min-bias" collisions ($p_T > 0.5$ GeV/c, $|\eta| < 1$). The "transverse" regions defined in Fig. 3 are shaded.

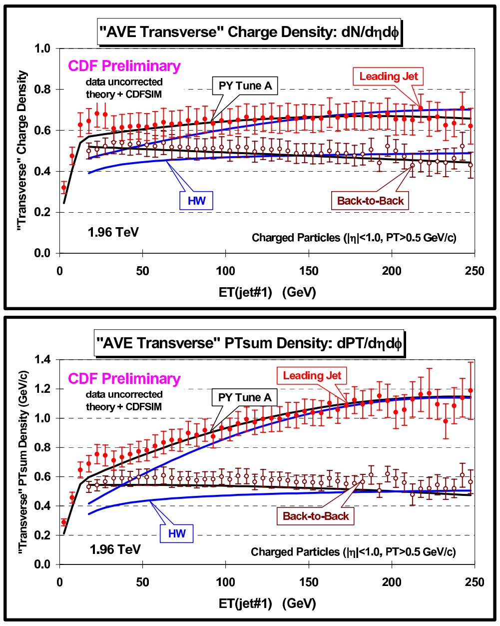

FIG. 6: Run 2 data on the average density of charged particles $dN_{chg}/d\phi d\eta$ (*top*) and the average PTsum density $dPT_{sum}/d\phi d\eta$ (*bottom*) for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for the "transverse" region for "leading jet" events and for "back-to-back" events defined in Fig. 4 as a function of the leading jet E_T compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM. The density in the "transverse" region corresponds to the average of the "transMAX" and "transMIN" densities.

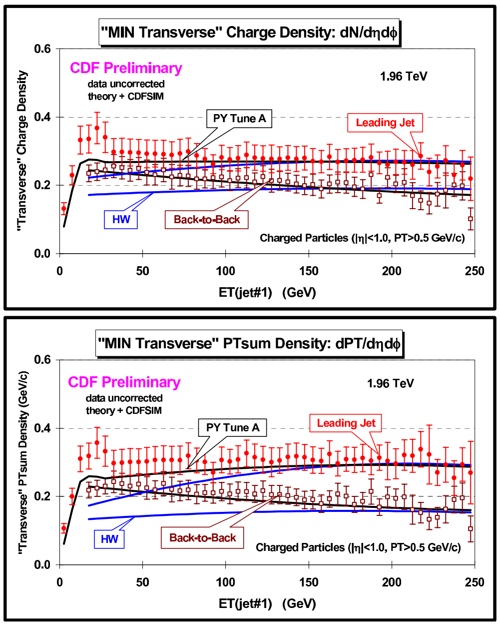

FIG. 7: Run 2 data on the average density of charged particles $dN_{chg}/d\phi d\eta$ (*top*) and the average PTsum density $dPT_{sum}/d\phi d\eta$ (*bottom*) for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the "transMIN" region defined in Fig. 5 for "leading jet" events and for "back-to-back" events defined in Fig. 4 as a function of the leading jet E_T compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

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 azimuthal angle. One can use the topological structure of hadron- hadron collisions to study the "underlying event" [2–6]. In Run 2 at CDF we study the "underlying event" 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".

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 $|\Delta\phi| < 60^\circ$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120^\circ$ and $|\eta| < 1$. The "transverse" region is defined by $60^\circ < |\Delta\phi| < 120^\circ$ and $|\eta| < 1$. The three regions "toward", "transverse" and "away" are shown in Fig. 3. Each region has an area in η-ϕ space 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 $|\eta(\text{jet\#1})| < 2$.

In the Run 2 analysis we consider two classes of events. As illustrated in Fig. 4, we refer to events in which there are no restrictions placed on the second and third highest E_T jets (jet#2 and jet#3) as "leading jet" events. Events with at least two jets with $E_T > 15$ GeV where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150^\circ$) with $E_T(\text{jet\#2})/E_T(\text{jet\#1}) > 0.8$ and $E_T(\text{jet\#3}) < 15$ GeV 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". Also, comparing the two "transverse" regions on an event-by-event basis provides a closer look at the "underlying event" and defining a variety of MAX and MIN "transverse" regions helps separate the "hard component" (initial and final-state radiation) from the "beam-beam remnants" 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, PTsum, of charged particles.

The data presented here are uncorrected and are compared with the PYTHIA Tune A [6] (with multiple parton interactions) and HERWIG [7] (with "beam-beam remnants" but no multiple parton interactions) after detector simulation (*i.e.*, after CDFSIM). Fig. 5 shows Run 2 data on the $\Delta\phi$ dependence of the density of charged particles, $dN_{chg}/d\phi d\eta$, and the scalar PTsum density, $dPT_{sum}/d\phi d\eta$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to the direction of the leading jet for $30 < E_T(\text{jet\#1}) < 70$ GeV (rotated to 270°) for "leading jet" and "back-to-back" events as defined in Fig. 4. Also shown is the average density of charged particles and the scalar PTsum density for "min-bias" collisions ($p_T > 0.5$ GeV/c, $|\eta| < 1$). The two "transverse" regions are very sensitive to the "underlying

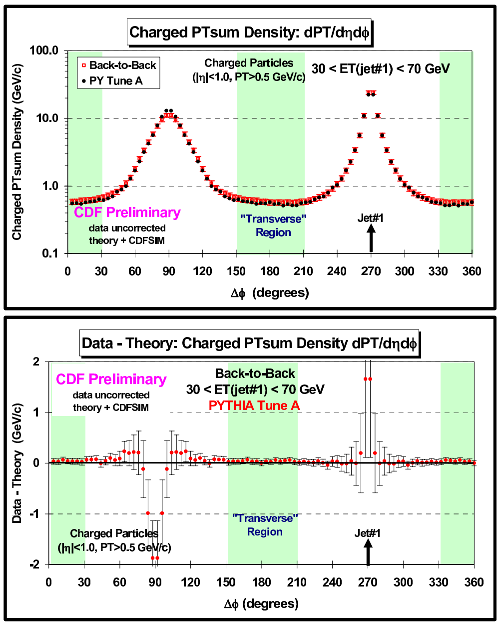

FIG. 8: Run 2 data (*top*) and data minus theory (*bottom*) for the $\Delta\phi$ dependence of the scalar PTsum density, $dPT_{sum}/d\phi d\eta$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to the direction of the leading jet with $30 < E_T(\text{jet\#1}) < 70$ GeV (rotated to 270°) for "back-to-back" events defined in Fig. 4. The theory corresponds to PYTHIA Tune A (after CDFSIM). The "transverse" region defined in Fig. 3 is shaded.

event" and as we saw in our previous analyses [2, 3] the "transverse" region in a hard scattering process has a higher density of charged particles and PTsum than an average "min-bias" collision. Also as expected, Fig. 5 indicates that there is less hard initial and final state radiation in the "transverse" region for the "back-to-back" events compared with "leading jet" events.

Fig. 6 compares the "leading jet" and "back-to-back" data on the average density of charged particles, $dN_{chg}/d\phi d\eta$, and the average PTsum density, $dPT_{sum}/d\phi d\eta$, in the "transverse" region (*i.e.*, average of "transMAX" and "transMIN") as a function of the leading jet E_T. Fig. 6 also shows the predictions of PYTHIA Tune A and HERWIG after CDFSIM. The "leading jet" and "back-to-back" events behave quite differently. For the "leading jet" case the densities rise with increasing E_T(jet#1), while for the "back-to-back" case they fall with increasing E_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 remnants" 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). HERWIG rises with increasing E_T(jet#1) even for the "back-to-back" events. PYTHIA Tune A agrees fairly well with both the "leading jet" and "back-to-back" events.

Fig. 7 compares PYTHIA Tune A and HERWIG with the "leading jet" and "back-to-back" data on the average density of charged particles, $dN_{chg}/d\phi d\eta$, and the average PTsum density, $dPT_{sum}/d\phi d\eta$, in the "transMIN" region as a function of the leading jet E_T. The "transMIN" densities are more sensitive to the "beam-beam remnants" and multiple parton interaction component of the "underlying event" [2, 3, 8]. The "back-to-back" data show a decrease in the "transMIN" densities with increasing E_T(jet#1) which is described 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 E_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. 8 and Fig. 9 compare the $\Delta\phi$ dependence of the charged particle density and the PTsum density relative to the direction of the leading jet with $30 < E_T(\text{jet\#1}) < 70$ GeV for "back-to-back" events with PYTHIA Tune A and HERWIG, respectively, after CDFSIM. Fig. 9 shows clearly that HERWIG (without multiple parton interaction) produces too few particles (and not enough PTsum) in the "transverse" region.

In Run 2 at CDF we examine the jet structure in "min-bias" collisions by studying correlations among the charged particles. As illustrated in Fig. 10, for "min-bias" collisions we examine correlations in azimuthal angle $\Delta\phi$ relative to the direction of the highest p_T charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the event, PTmax. The $\Delta\phi$ dependence of

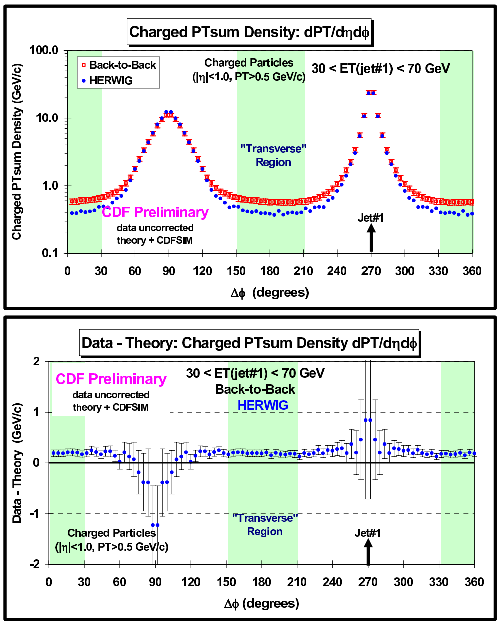

FIG. 9: Run 2 data (*top*) and data minus theory (*bottom*) for the $\Delta\phi$ dependence of the scalar PTsum density, $dPT_{sum}/d\phi d\eta$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to the direction of the leading jet with $30 < E_T(\text{jet}\#1) < 70$ GeV (rotated to $270°$) for "back-to-back" events defined in Fig. 4. The theory corresponds to HERWIG (after CDFSIM). The "transverse" region defined in Fig. 3 is shaded.

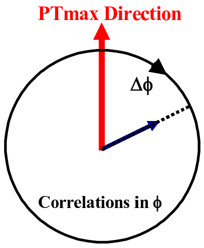

FIG. 10: Illustration of correlations in azimuthal angle $\Delta\phi$relative to the direction of the highest p_T charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the event, PTmax. The $\Delta\phi$dependence of the "associated" density of particles, $dN_{chg}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including PTmax) are plotted relative to the direction of PTmax.

the "associated" density of charged particles, $dN_{chg}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including PTmax) are plotted relative to the direction of PTmax which is rotated to 180°. The "associated" density is a measure of the particles accompanying the maximum p_T charged particle. Fig. 11 shows the Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles relative to the direction of PTmax for $PT\text{max} > 0.5$ GeV/c, $PT\text{max} > 1.0$ GeV/c, and $PT\text{max} > 2.0$ GeV/c for "min-bias" collisions at 1.96 TeV. Fig. 11 indicates "jet structure" in "min-bias" collisions. The density of charged particles "associated" with PTmax is larger than the average density of charged particles in "min-bias" collisions. Fig. 11 shows the "birth" of jet#1 in "min-bias" collisions. One can also see the "birth" of jet#2, which results in the rise in the number density in the region opposite PTmax. Fig. 11 also shows a rapid increase in the activity in the "transverse" region as PTmax increases.

The jet structure in the "underlying event" is examined by studying correlations among the charged particles in the "transverse" region in "back-to-back" events. As illustrated in Fig. 12, we examine correlations in azimuthal angle $\Delta\phi$ relative to the direction of the highest p_T charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the "transverse" region, PTmax$T$. On an event-by-event basis, the direction of the leading jet (highest E_T jet) in the event, jet#1, is used to define the two "transverse" regions $60° < \Delta\phi < 120°$ and $60° < -\Delta\phi < 120°$, with PTmax$T$ being the highest p_T charged particle in these two regions. The $\Delta\phi$ dependence of the "associated" density of charged

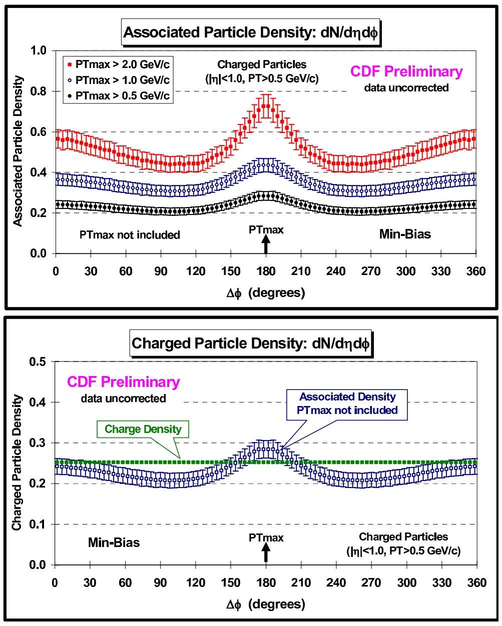

FIG. 11: (*top*) Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{chg}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including PTmax) relative to the direction of PTmax (rotated to 180°) with $PT\max > 0.5$ GeV/c, $PT\max > 1.0$ GeV/c, and $PT\max > 2.0$ GeV/c for "min-bias" collisions at 1.96 TeV. (*bottom*) $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{chg}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including PTmax) relative to the direction ofPTmax (rotated to 180°) compared with the average density of charged particles, $dN_{chg}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "min-bias" collisions at 1.96 TeV.

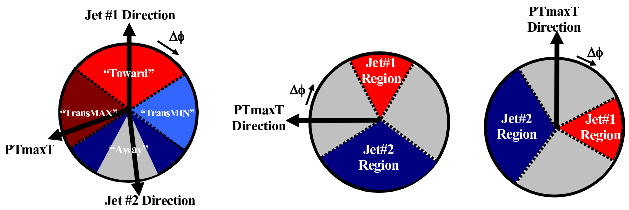

FIG. 12: (*left*) Illustration of correlations in azimuthal angle $\Delta\phi$ relative to the direction of the highest p_T charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the "transverse" region, $PT\max T$ for "back-to-back" events defined in Fig. 4. On an event-by-event basis, the direction of the leading jet (highest E_T jet) in the event, jet#1, is used to define the two "transverse" regions, $60° < \Delta\phi < 120°$ and $60° < -\Delta\phi < 120°$, with $PT\max T$ being the highest p_T charged particle in these two regions. (*middle*) The $\Delta\phi$ dependence of the "associated" density of charged particles. $dN_{chg}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including $PT\max T$) are plotted relative to the direction of $PT\max T$. (*right*) The direction of positive $\Delta\phi$ is chosen so that jet#1 is always to the right of $PT\max T$ which is rotated to 180°.

particles, $dN_{chg}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including $PT\max T$) are plotted relative to the direction of $PT\max T$ which is rotated to 180°. The direction of positive $\Delta\phi$ (clockwise versus counter-clockwise) is chosen, on an event-by-event basis so that jet#1 always lies in the range $240° < \Delta\phi < 300°$. The "jet#1 region" and the "jet#2 region" region are shaded in Fig. 13 which shows the Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{chg}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$, for charged particles relative to $PT\max T$ for $PT\max T > 0.5$ GeV/c, $PT\max T > 1.0$ GeV/c, and $PT\max T > 2.0$ GeV/c for "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV.

Fig. 13 shows the "birth" of jet#3 in the "transverse" region. One can also see the "birth" of jet#4, which results in the rise in the number density in the region 180° from $PT\max T$ (*e.g.*, the region opposite to $PT\max T$). Fig. 14 is a polar plot comparing the $\Delta\phi$ dependence of the density of charged particles relative to the direction of the leading jet (rotated to 0°) with the "associated" density of charged particles relative the direction of $PT\max T$(rotated to 270°,

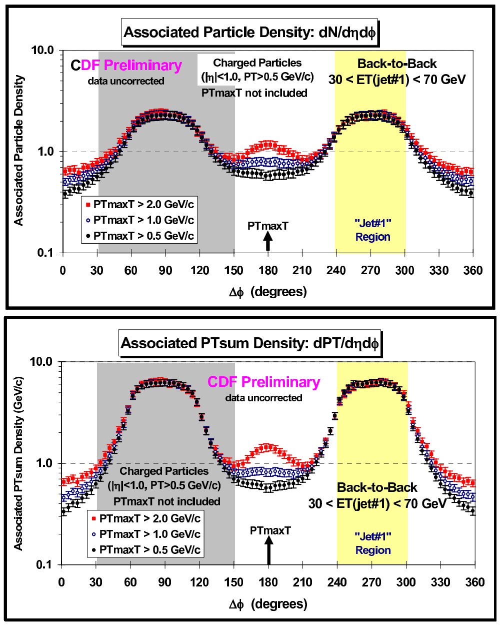

FIG. 13: Run 2 data on the $\Delta\phi$dependence of the“associated” density of charged particles $dN_{chg}/d\phi d\eta$ (*top*) and the “associated” scalar PTsum density $dPT_{sum}/d\phi d\eta$ (*bottom*) for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT\max T$) relative to the direction of $PT\max T$ (rotated to 180°) for $PT\max T > 0.5$ GeV/c, $PT\max T > 1.0$ GeV/c, and $PT\max T > 2.0$ GeV/c with $30 < E_T$(jet#1) < 70 GeV for “back-to-back” events defined in Fig. 4. The “jet#1” and the “jet#2” regions shown in Fig. 12 are shaded.

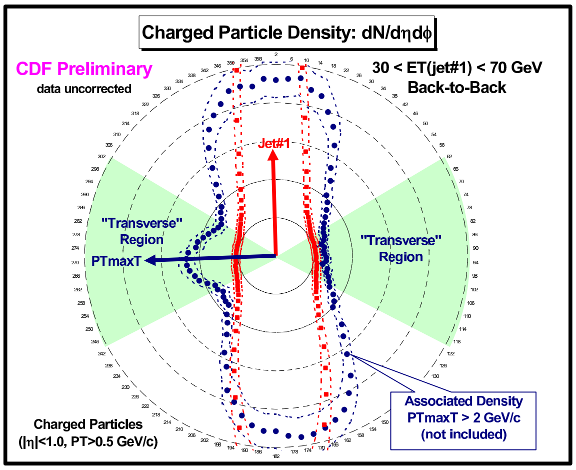

FIG. 14: Polar plot showing the $\Delta\phi$ dependence of the density of charged particles, $dN_{chg}/d\phi d\eta$ with $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to the direction of the leading jet for $30 < E_T$(jet#1) < 70 GeV (rotated to 0°) for “back-to-back” events and the “associated” density of charged particles, $dN_{chg}/d\phi d\eta$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ (not including PTmaxT) relative to the direction of $PT\max T$ (rotated to 270°) for $PT\max T > 2.0$ GeV/c. The errors (combined statistical plus systematic) are indicated by dashed lines. The “transverse” region defined in Fig. 3 is shaded.

not including $PT\max T$) for “back-to-back” events with $30 < E_T$(jet#1) < 70 GeV. It is interesting to speculate as to whether the evidence for jet#3 and jet#4 come from 2-to-2 parton-parton scattering combined with gluon radiation (*i.e.*, 2-to-3 or 2-to-4 subprocesses) or whether there is an increased four jet topology arising from multiple parton interactions (*i.e.*, two 2-to-2 parton- parton scatterings).

Fig. 15 and Fig. 16 compare the $\Delta\phi$ dependence of the “associated” PTsum density relative to the direction of PTmax with $PT\max T > 0.5$ GeV/c (not including $PT\max T$) for “back-to-back” events with $30 < E_T$(jet#1) $<$ 70 GeV with PYTHIA Tune A and HERWIG, respectively, after CDFSIM. PYTHIA Tune A with multiple parton

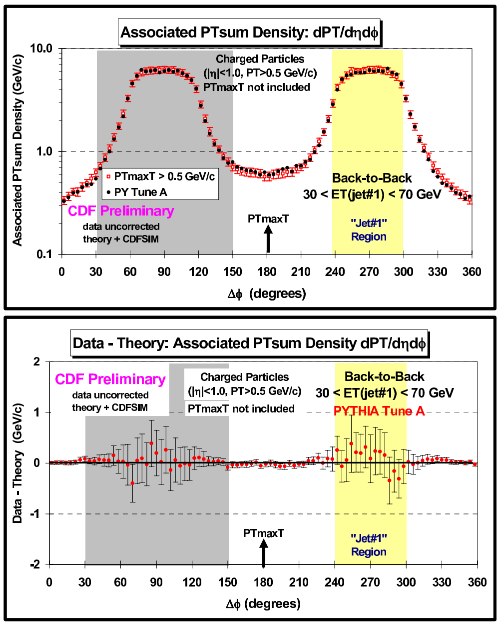

FIG. 15: Run 2 data (*top*) and data minus theory (*bottom*) for the $\Delta\phi$ dependence of the"associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$ for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ (not including $PT\max T$) relative to the direction of $PT\max T$ (rotated to 180°) with $30 < E_T(\text{jet}\#1) < 70\,\mathrm{GeV}$ for "back-to-back" events defined in Fig. 4. The theory corresponds to PYTHIA Tune A (after CDFSIM). The "jet#1" and the "jet#2" regions defined in Fig. 12 are shaded.

interactions does an excellent job describing the data. HERWIG does not have enough activity in the direction of $PT\max T$ and also in the region opposite to $PT\max T$.

Fig. 17 and Fig. 18 compare the $\Delta\phi$ dependence of the "associated" PTsum density relative to the direction of $PT\max T$ with $PT\max T > 2.0\,\mathrm{GeV/c}$ (not including $PT\max T$) for "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70\,\mathrm{GeV}$ with PYTHIA Tune A and HERWIG, respectively, after CDFSIM. PYTHIA Tune A with multiple parton interactions does an excellent job describing the data. Here HERWIG does have enough activity in the direction of $PT\max T$ but does not have enough activity in the region opposite to $PT\max T$ (*i.e.*, jet#4 region). On the other hand, PYTHIA Tune A describes both the region in the direction of $PT\max T$ (*i.e.*, jet#3 region) and the region opposite to $PT\max T$ (*i.e.*, jet#4 region). One can speculate that the increased four jet topology in PYTHIA Tune A arising from multiple parton interactions (*i.e.*, two 2-to-2 parton-parton scatterings) is resulting in the better agreement with the data for PYTHIA Tune A over HERWIG which does not have multiple parton interactions and thus is trying to fit the data in Fig. 18 with three jet topologies (*i.e.*, 2-to-2 parton-parton scattering plus gluon radiation). Of course the next step would be to look directly at four jet topologies in the data and to identify an enhanced component of the four jet topology due to two independent 2-to-2 parton- parton scatterings one with two high E_T jets and the other with two low E_T jets.

[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] "The Underlying Event in Hard Interactions at the Tevatron Proton-Antiproton Collider", The CDF Collaboration (D. Acosta et al.), *to appear in Phys. Rev. D*.

[4] "The Underlying Event in Large Transverse Momentum Charged Jet and Z-boson Production at 1.8 TeV", talk presented by R. Field at DPF2000, Columbus, OH, August 11, 2000.

[5] "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.

[6] "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

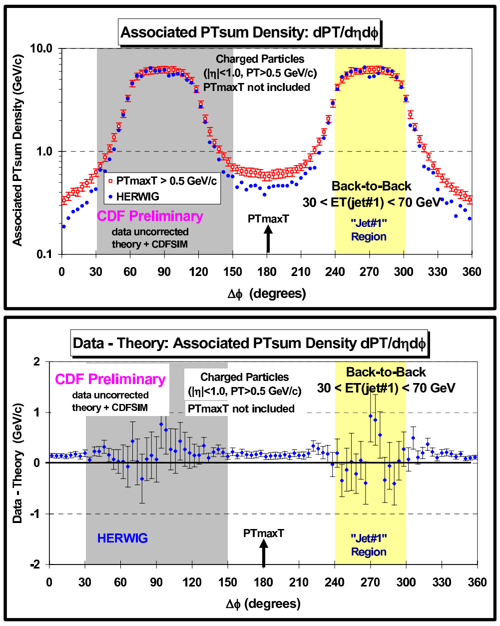

FIG. 16: Run 2 data (*top*) and data minus theory (*bottom*) for the $\Delta\phi$ dependence of the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$ for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ (not including $PT\max T$) relative to the direction of $PT\max T$ (rotated to 180°) with $30 < E_T(\mathrm{jet\#1}) < 70\,\mathrm{GeV}$ for "back-to-back" events defined in Fig. 4. The theory corresponds to HERWIG (after CDFSIM). The "jet#1" and the "jet#2" regions defined in Fig. 12 are shaded.

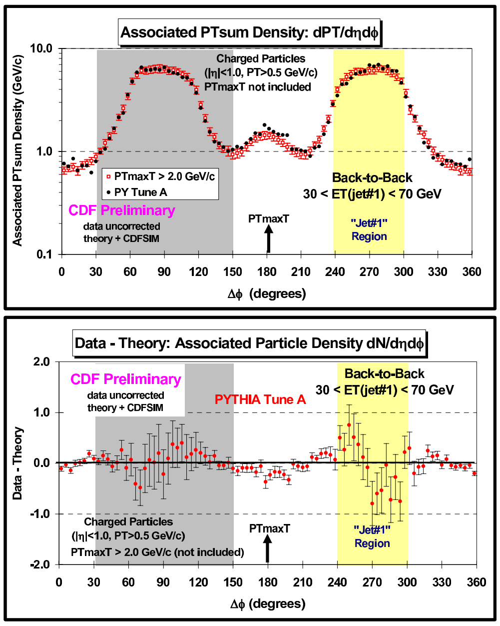

FIG. 17: Run 2 data (*top*) and data minus theory (*bottom*) for the $\Delta\phi$ dependence of the "associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$ for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ (not including $PT\max T$) relative to the direction of $PT\max T$ (rotated to 180°) with $PT\max T > 2.0\,\mathrm{GeV/c}$ and $30 < E_T(\mathrm{jet\#1}) < 70\,\mathrm{GeV}$ for "back-to-back" events defined in Fig. 4. The theory corresponds to PYTHIA Tune A (after CDFSIM). The "jet#1" and the "jet#2" regions defined in Fig. 12 are shaded.

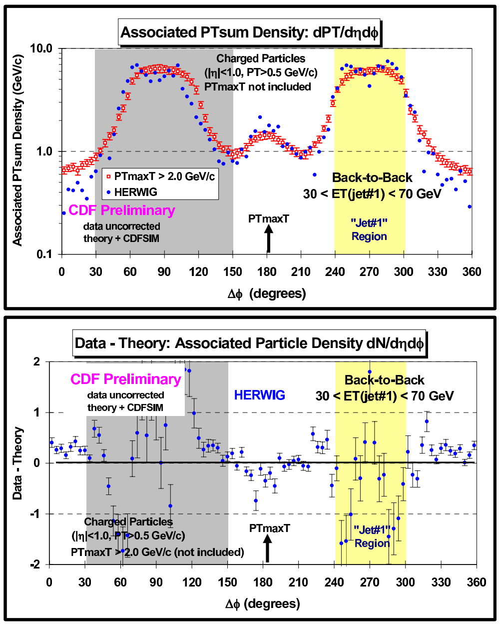

FIG. 18: Run 2 data (*top*) and data minus theory (*bottom*) for the $\Delta\phi$ dependence of the"associated" scalar PTsum density, $dPT_{sum}/d\phi d\eta$ for charged particles with $p_T > 0.5\,\mathrm{GeV/c}$ and $|\eta| < 1$ (not including $PT\max T$) relative to the direction of $PT\max T$ (rotated to 180°) with $PT\max T > 2.0\,\mathrm{GeV/c}$ and $30 < E_T(\mathrm{jet\#1}) < 70\,\mathrm{GeV}$ for "back-to-back" events defined in Fig. 4. The theory corresponds to HERWIG (after CDFSIM). The "jet#1" and the "jet#2" regions defined in Fig. 12 are shaded.

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

[7] 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).

[8] "Hard Underlying Event Corrections to Inclusive Jet Cross-Sections", Jon Pumplin, Phys. Rev. **D57**, 5787 (1998).