Vol. 36 (2005) ACTA PHYSICA POLONICA B No 2

MIN-BIAS AND THE UNDERLYING EVENT IN RUN 2 AT CDF*

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(Received October 7, 2004)

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 $p_{\rm T}$ sum density relative to the direction of the leading jet for "leading jet" and "back-to-back" events are studied. The "jet structure" in the "underlying event" and in "min-bias" collosions is studied by defining "associated" charged particle densities that measure the number of charged particles accompanying the maximum $p_{\rm T}$ charged particle in the "transverse" region or the maximum $p_{\rm T}$ particle in the event.

PACS numbers: 13.85.–t

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, $p_{\rm T}$(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. 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. 1 also 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

* Presented at the XXXIV International Symposium on Multiparticle Dynamics, Sonoma County, California, USA, July 26–August 1, 2004.

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". 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".

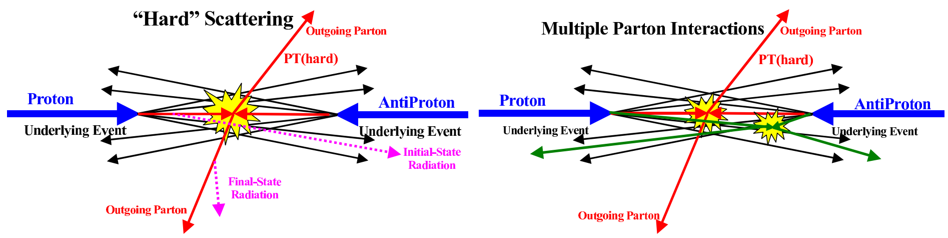


Fig. 1. (left) Illustration of the way QCD Monte-Carlo models simulate a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, p_{T}(hard), has occurred. The resulting event contains particles that originate from the two outgoing partons (plus initial and final-state 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. (right) 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".

The direction of the leading jet, jet#1, is used to define correlations in the azimuthal angle, ϕ. The "transverse" region is defined by $60° < |\Delta\phi| < 120°$ and $|\eta| < 1$. 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 $p_{\mathrm{T}} > 0.5$ GeV/c and $|\eta| < 1$, but allow the leading jet that is used to define the "transverse" region to have $|\eta(\mathrm{jet}\#1)| < 2$.

In the Run 2 analysis we consider two classes of events. As illustrated in Fig. 2, we refer to events in which there are no restrictions placed on the second and third highest E_{T} jets as "leading jet" events. Events with at least two jets with $E_{\mathrm{T}} > 15$ GeV where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150°$) with $E_{\mathrm{T}}(\mathrm{jet}\#2)/E_{\mathrm{T}}(\mathrm{jet}\#1) > 0.8$ and $E_{\mathrm{T}}(\mathrm{jet}\#3) < 15$ 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

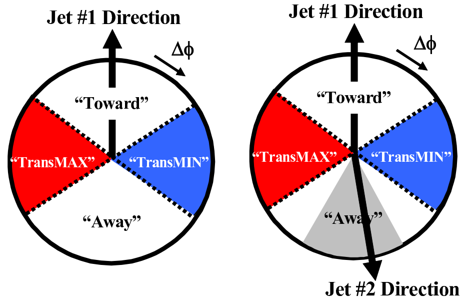


Fig. 2. Illustration of correlations in azimuthal angle ϕ relative to the direction of the leading jet (highest E_{T} jet) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\mathrm{jet1}}$ is the relative azimuthal angle between charged particles and the direction of jet#1. On an event by event basis, we define "transMAX" ("transMIN") to be the maximum (minimum) of the two "transverse" regions, $60° < \Delta\phi < 120°$ and $60° < -\Delta\phi < 120°$. "TransMAX" and "transMIN" each have an area in η-ϕ space of $\Delta\eta\Delta\phi = 4\pi/6$. The overall "transverse" region 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 $E_{\mathrm{T}} > 15\,\mathrm{GeV}$ where the leading two jets are nearly "back-to-back" ($|\Delta\phi| > 150°$) with $E_{\mathrm{T}}(\mathrm{jet\#2})/E_{\mathrm{T}}(\mathrm{jet\#1}) > 0.8$ and $E_{\mathrm{T}}(\mathrm{jet\#3}) < 15\,\mathrm{GeV}$ are referred to as "back-to-back" events (right).

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 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. 3 shows Run 2 data on the $\Delta\phi$ dependence of the density of charged particles, $dN_{\mathrm{chg}}/d\phi d\eta$, and the scalar PTsum density, $dPT_{\mathrm{sum}}/d\phi d\eta$, for charged particles relative to the direction of the leading jet for $30 < E_{\mathrm{T}}(\mathrm{jet\#1}) < 70\,\mathrm{GeV}$ (rotated to 270°) for "leading jet" and "back-to-back" events as defined in Fig. 2. Also shown is the average density of charged particles and the scalar PTsum density for

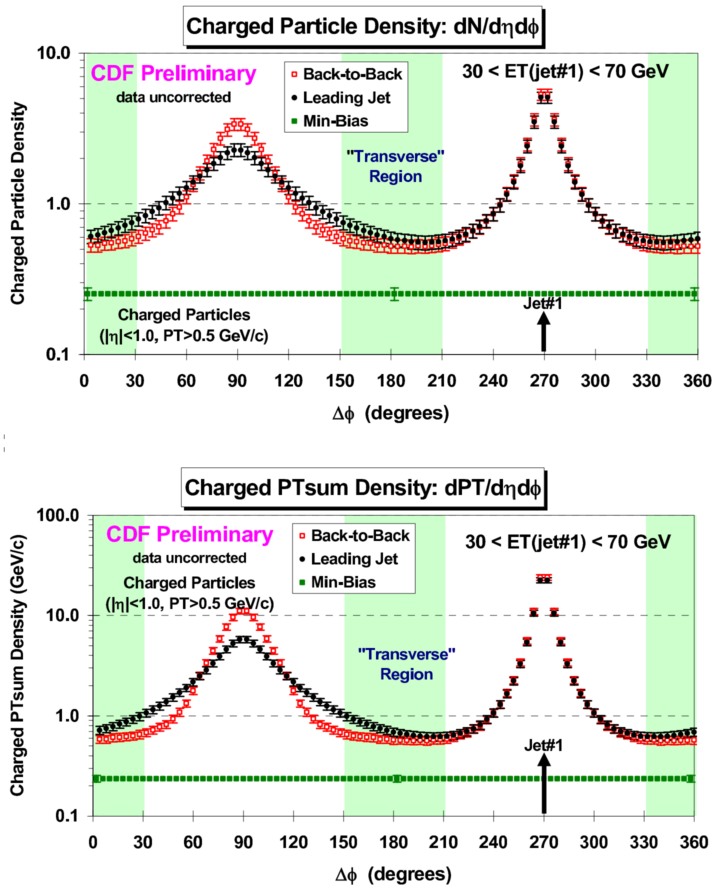
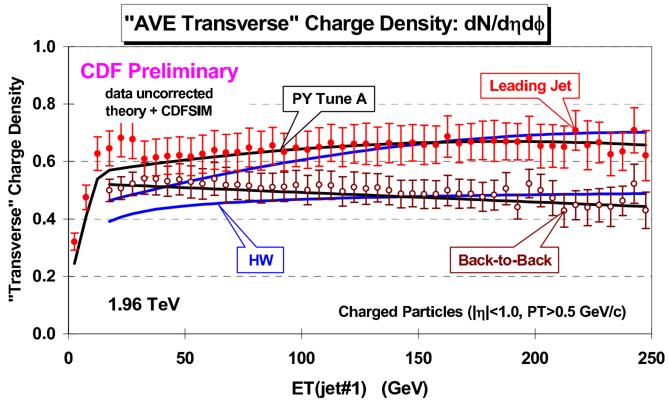


Fig. 3. Run 2 data on the $\Delta\phi$ dependence of the density of charged particles, $dN_{\rm chg}/d\phi d\eta$ (top), and the scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$ (bottom), for charged particles ($p_{\rm T} > 0.5$ GeV/c, $|\eta| < 1$) relative to the direction of the leading jet for $30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

"min-bias" collisions. The two "transverse" regions are very sensitive to the "underlying 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. 3 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.



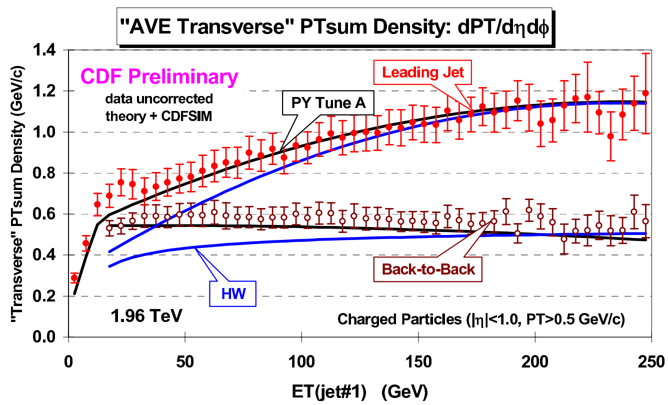


Fig. 4. Run 2 data on the average density of charged particles $dN_{\mathrm{chg}}/d\phi d\eta$ (top) and the average PTsum density $dPT_{\mathrm{sum}}/d\phi d\eta$ (bottom) for charged particles ($p_{\mathrm{T}} > 0.5\,\mathrm{GeV}/c$, $|\eta| < 1$) for the "transverse" region for "leading jet" events and for "back-to-back" events defined in Fig. 2 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. 4 compares the "leading jet" and "back-to-back" data on the average density of charged particles, $dN_{\mathrm{chg}}/d\phi d\eta$, and the average PTsum density, $dPT_{\mathrm{sum}}/d\phi d\eta$, in the "transverse" region (*i.e.* average of "transMAX" and "transMIN") as a function of the leading jet E_{T}. Fig. 4 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"

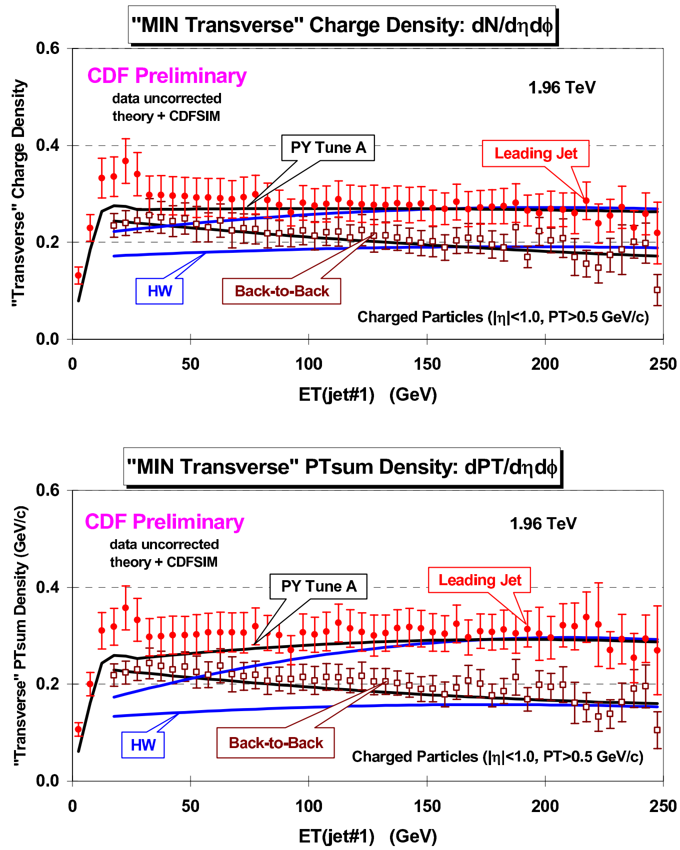


Fig. 5. Run 2 data on the average density of charged particles $dN_{\mathrm{chg}}/d\phi d\eta$ (top) and the average PTsum density $dPT_{\mathrm{sum}}/d\phi d\eta$ (bottom) for charged particles ($p_{\mathrm{T}} > 0.5\,\mathrm{GeV}/c$, $|\eta| < 1$) in the "transMIN" region defined in Fig. 2 for "leading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

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. 5 compares PYTHIA Tune A and HERWIG with the "leading jet" and "back-to-back" data on the average density of charged particles,

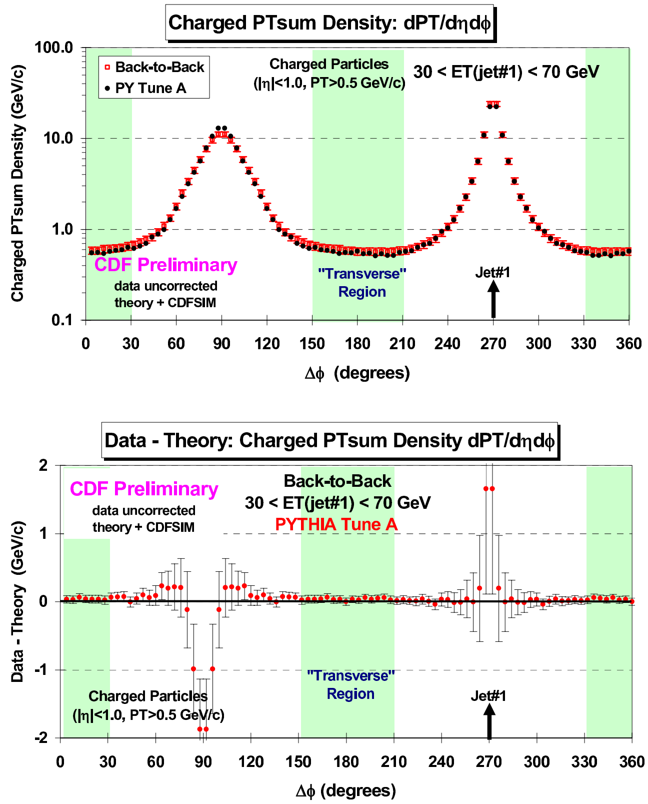


Fig. 6. Run 2 data (top) and data minus theory (bottom) for the $\Delta\phi$ dependence of the scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$ for charged particles ($p_{\rm T} > 0.5\,{\rm GeV}/c$, $|\eta| < 1$) relative to the direction of the leading jet with $30 < E_{\rm T}({\rm jet}\#1) < 70\,{\rm GeV}$ (rotated to 270°) for "back-to-back" events. The theory corresponds to PYTHIA Tune A (after CDFSIM). The "transverse" regions defined in Fig. 2 are shaded.

$dN_{\rm chg}/d\phi d\eta$, and the average PTsum density, $dPT_{\rm sum}/d\phi d\eta$, in the "transMIN" region as a function of the leading jet $E_{\rm T}$. 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 $E_{\rm T}({\rm jet}\#1)$ 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 $E_{\rm T}({\rm jet}\#1)$ 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).

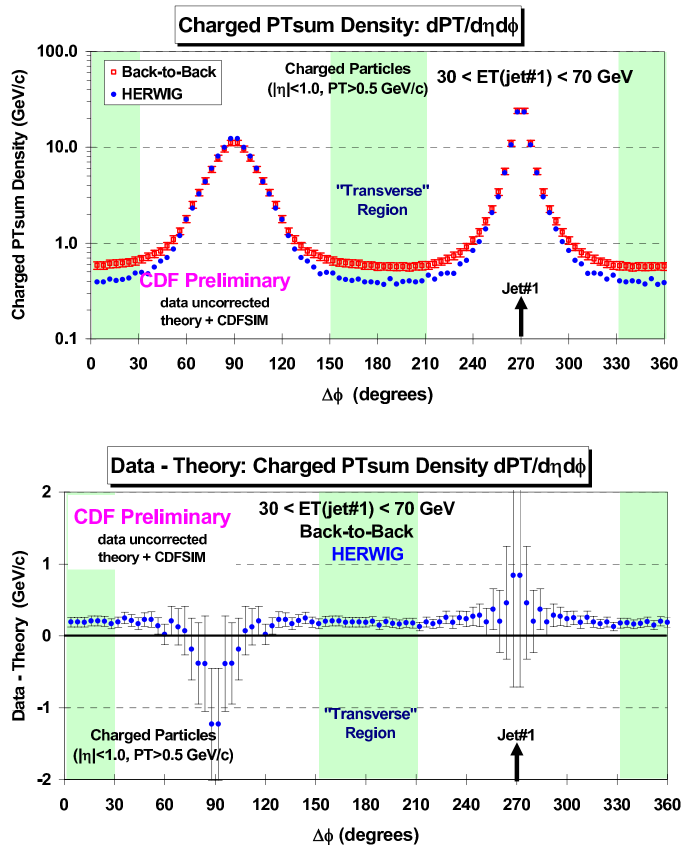


Fig. 7. Run 2 data (top) and data minus theory (bottom) for the $\Delta\phi$ dependence of the scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$ for charged particles ($p_{\rm T} > 0.5$ GeV/c, $|\eta| < 1$) relative to the direction of the leading jet with $30 < E_{\rm T}(\text{jet}\#1) < 70$ GeV (rotated to 270°) for "back-to-back" events. The theory corresponds to HERWIG (after CDFSIM). The "transverse" regions defined in Fig. 2 are shaded.

Fig. 6 and Fig. 7 compare the $\Delta\phi$ dependence of the charged particle density and the PTsum density relative to the direction of the leading jet with $30 < E_{\rm T}(\text{jet}\#1) < 70$ GeV for "back-to-back" events with PYTHIA Tune A and HERWIG, respectively, after CDFSIM. Fig. 7 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. For "min-bias" collisions we examine correlations in azimuthal angle $\Delta\phi$ relative to the direction of the highest $p_{\rm T}$ charged particle in the event, PTmax. The $\Delta\phi$ dependence of the

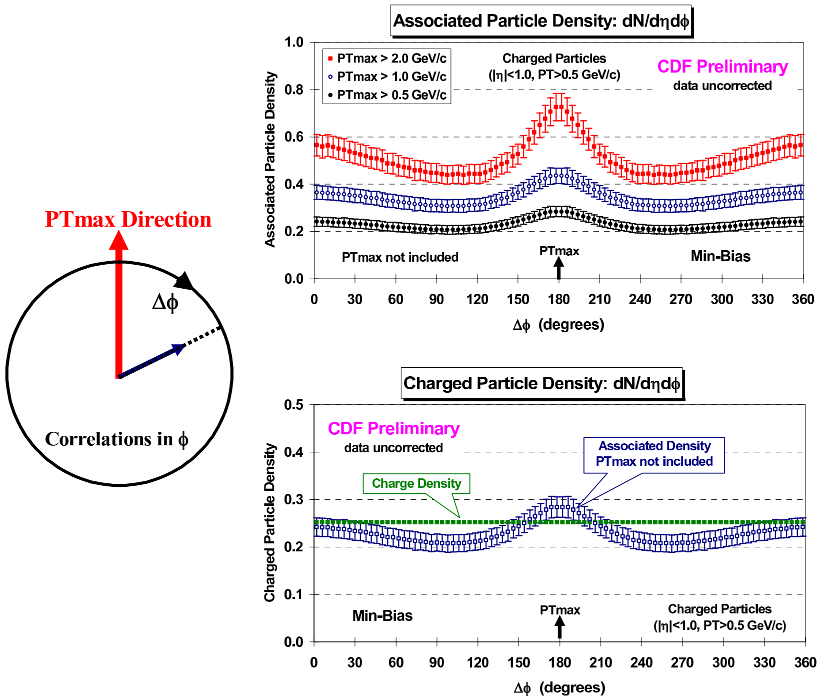


Fig. 8. (top) Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{\rm chg}/d\phi d\eta$, with $p_{\rm T} > 0.5\,{\rm GeV}/c$ and $|\eta| < 1$ (not including PTmax) relative to the direction of PTmax (rotated to 180°) with $PT{\rm max} >$ 0.5 GeV/c, $PT{\rm max} > 1.0$ GeV/c, and $PT{\rm max} > 2.0$ GeV/c for "min-bias" collisions at 1.96 TeV. (bottom) $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{\rm chg}/d\phi d\eta$, with $p_{\rm T} > 0.5\,{\rm GeV}/c$ and $|\eta| < 1$ (not including PTmax) relative to the direction ofPTmax (rotated to 180°) compared with the average density of charged particles, $dN_{\rm chg}/d\phi d\eta$, with $p_{\rm T} > 0.5\,{\rm GeV}/c$ and $|\eta| < 1$ for "min-bias" collisions at 1.96 TeV.

"associated" density of charged particles, $dN_{\rm chg}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$, for charged particles (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 $p_{\rm T}$ charged particle. Fig. 8 shows the Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles relative to the direction of PTmax for $PT{\rm max} > 0.5$ GeV/c, $PT{\rm max} > 1.0$ GeV/c, and $PT{\rm max} > 2.0$ GeV/c for "min-bias" collisions at 1.96 TeV. Fig. 8 indicates "jet structure" in "min-bias" collisions. The density of charged particles "associated" with PTmax is larger than the average density of charged particles

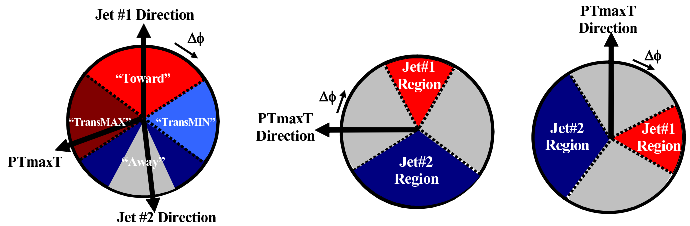


Fig. 9. (left) Illustration of correlations in azimuthal angle $\Delta\phi$ relative to the direction of the highest $p_{\rm T}$ charged particle ($p_{\rm T} > 0.5\,{\rm GeV}/c$, $|\eta| < 1$) in the "transverse" region, $PT{\rm max}T$ for "back-to-back" events defined in Fig. 2. On an event-by-event basis, the direction of the leading jet (highest $E_{\rm T}$ jet) in the event, jet#1, is used to define the two "transverse" regions, $60° < \Delta\phi < 120°$ and $60° < -\Delta\phi < 120°$, with $PT{\rm max}T$ being the highest $p_{\rm T}$ charged particle in these two regions. (middle) The $\Delta\phi$ dependence of the "associated" density of charged particles. $dN_{{\rm ch}g}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$, for charged particles with $p_{\rm T} > 0.5\,{\rm GeV}/c$ and $|\eta| < 1$ (not including $PT{\rm max}T$) are plotted relative to the direction of $PT{\rm max}T$. (right) The direction of positive $\Delta\phi$ is chosen so that jet#1 is always to the right of $PT{\rm max}T$ which is rotated to 180°.

in "min-bias" collisions. Fig. 8 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. 8 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. 9, we examine correlations in azimuthal angle $\Delta\phi$ relative to the direction of the highest $p_{\rm T}$ charged particle in the "transverse" region, $PT{\rm max}T$. On an event-by-event basis, the direction of the leading jet (highest $E_{\rm T}$ jet) in the event, jet#1, is used to define the two "transverse" regions $60° < \Delta\phi < 120°$ and $60° < -\Delta\phi < 120°$, with $PT{\rm max}T$ being the highest $p_{\rm T}$ charged particle in these two regions. The $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{{\rm ch}g}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$, for charged particles (not including $PT{\rm max}T$) are plotted relative to the direction of $PT{\rm max}T$ 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. 10 which shows the Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles, $dN_{{\rm ch}g}/d\phi d\eta$, and the "associated" scalar PTsum density, $dPT_{\rm sum}/d\phi d\eta$, for charged particles relative to $PT{\rm max}T$ for $PT{\rm max}T > 0.5$ GeV/c, $PT{\rm max}T > 1.0$ GeV/c, and $PT{\rm max}T > 2.0$ GeV/c for "back-to-back" events with $30 < E_{\rm T}({\rm jet}\#1) < 70\,{\rm GeV}$.

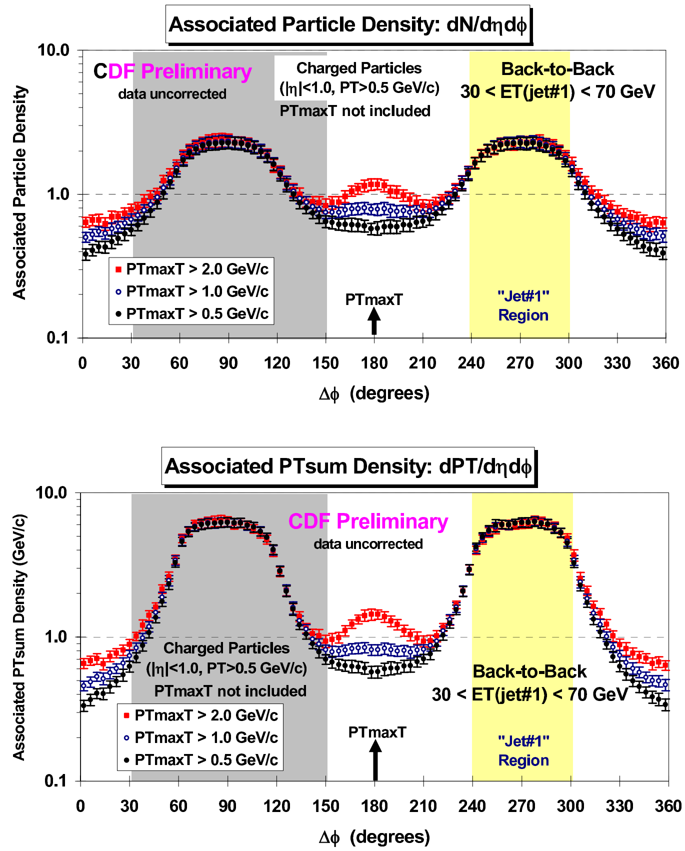


Fig. 10. Run 2 data on the $\Delta\phi$ dependence of the "associated" density of charged particles $dN_{\rm chg}/d\phi d\eta$ (top) and the "associated" scalar PTsum density $dPT_{\rm sum}/d\phi d\eta$ (bottom) for charged particles ($p_{\rm T} > 0.5\,{\rm GeV}/c$, $|\eta| < 1$, not including $PT{\rm max}T$) relative to the direction of $PT{\rm max}T$ (rotated to 180°) for $PT{\rm max}T > 0.5{\rm GeV}/c$, $PT{\rm max}T > 1.0$ GeV/c, and $PT{\rm max}T > 2.0$ GeV/c with $30 < E_{\rm T}({\rm jet}\#1) < 70\,{\rm GeV}$ for "back-to-back" events defined in Fig. 2. The "jet#1" and the "jet#2" regions shown in Fig. 9 are shaded.

Fig. 10 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 $PT{\rm max}T$ (*e.g.* the region opposite to $PT{\rm max}T$). 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). Of course the next step is 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. This analysis is currently underway at CDF and I hope to report the results soon.

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