Using MAX/MIN Transverse Regions and Associated Densities to Study the Underlying Event

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Abstract

We study the behavior of the charged particle (p_T > 0.5 GeV/c, $|\eta|$ < 1) component of the "underlying event" in hard scattering 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 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 remnant" component. In addition, selecting events with at least two jets that are nearly back-to-back ($\Delta\phi_{12} > 150^o$) allows for a more detailed study of the "beam-beam remnant" component 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. 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.

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

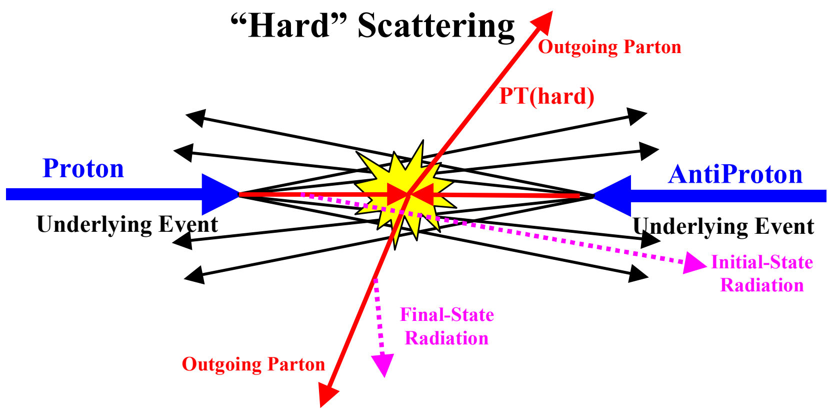


Fig. 1. Illustration of the way QCD Monte-Carlo models simulate a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, P_T(hard), has occurred. The resulting event contains particles that originate from the two outgoing partons (plus initial and final-state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

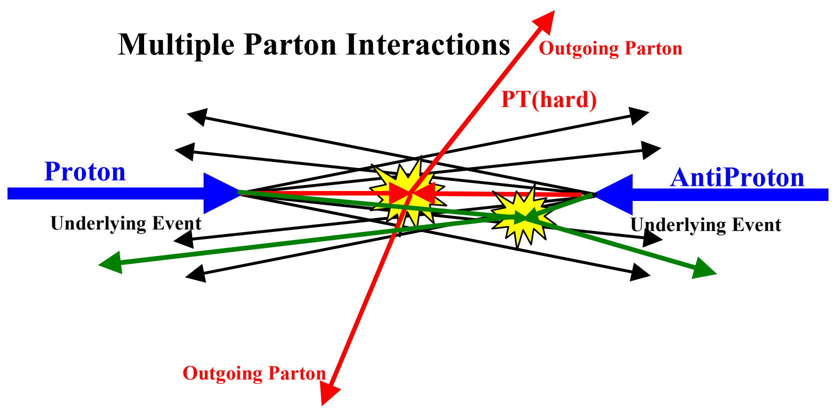


Fig. 2. Illustration of the way PYTHIA models the "underlying event" in proton-antiproton collision by including multiple parton interactions. In addition to the hard 2-to-2 parton-parton scattering with transverse momentum, P_T(hard), there is a second "semi-hard" 2-to-2 parton-parton scattering that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

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 azimuthal angle. One can use the topological structure of hadron-hadron collisions to study the "underlying event" [2-4]. We will study the "underlying event" in the Run 2 "min-bias" and jet trigger data samples 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, $\Delta\phi$. The angle $\Delta\phi = \phi - \phi_{jet\#1}$ is the relative azimuthal angle between a charged particle and the direction of jet#1. The "toward" region is defined by $|\Delta\phi| < 60^o$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120^o$ and $|\eta| < 1$. The "transverse" region is defined by $60^o < |\Delta\phi| < 120^o$ 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 $|\eta(\text{jet\#1})| < 2$.

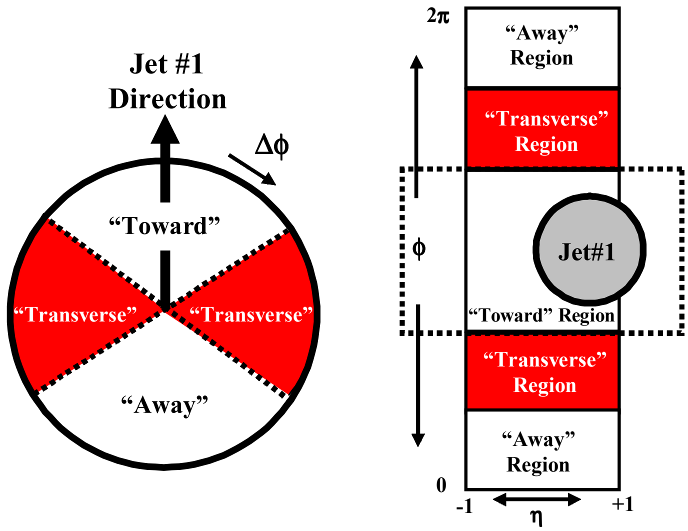


Fig. 3. Illustration of correlations in azimuthal angle Δφ relative to the direction of the leading jet (JetClu, R = 0.7) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\text{jet\#1}}$ is the relative azimuthal angle between charged particles and the direction of jet#1. The "toward" region is defined by $|\Delta\phi| < 60^o$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120^o$ and $|\eta| < 1$. The "transverse" region is defined by $60^o < |\Delta\phi| < 120^o$ and $|\eta| < 1$. Each of the three regions "toward", "transverse", and "away" and has an overall 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 $|\eta(\text{jet\#1})| < 2$.

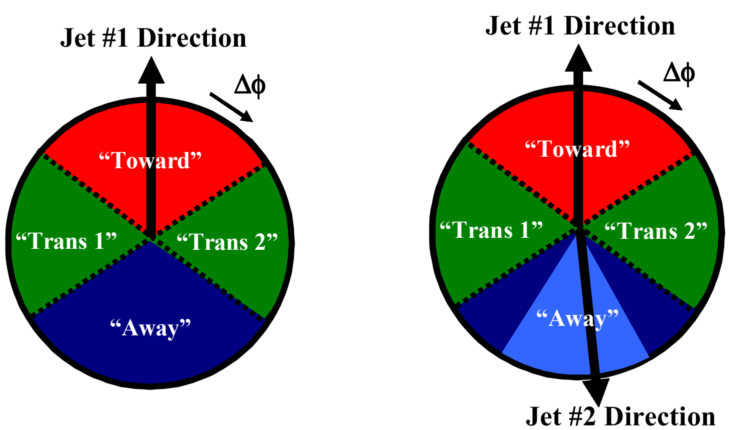


Fig. 4. Illustration of correlations in azimuthal angle Δφ relative to the direction of the leading jet (highest E_T jet) in the event, jet#1. The angle $\Delta\phi = \phi - \phi_{\text{jet\#1}}$ is the relative azimuthal angle between charged particles and the direction of jet#1. The "toward" region is defined by $|\Delta\phi| < 60^o$ and $|\eta| < 1$, while the "away" region is $|\Delta\phi| > 120^o$ and $|\eta| < 1$. The two "transverse" regions $60^o < \Delta\phi < 120^o$ and $60^o < -\Delta\phi < 120^o$ 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 where the leading two jets are nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with $E_T(\text{jet\#2})/E_T(\text{jet\#1}) > 0.8$ are referred to as "back-to-back" events (*right*).

This is a continuation of our previous Run 2 analysis [5] where we compared the Run 2 data with our published Run 1 analysis [2]. However, our previous Run 2 analysis considered only the overall "transverse" region defined in Fig. 3. Here we look in more detail at the two transverse regions defined in Fig. 4. The overall "transverse" region 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" and defining a variety of MAX and MIN "transverse" regions helps separate the "hard component" (initial and final-state radiation) from the "beam-beam remnant" component. Our previous Run 2 analysis did not put any restrictions on the second highest E_T jet in the event. Here we refer to 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" only considered "leading jet" events. In this analysis we define a second class of events. Events with at least two jets where the leading two jets are nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with E_T(jet#2)/E_T(jet#1) > 0.8 are referred to as "back-to-back" 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 remnant" and the multiple parton scattering component of the "underlying event".

In this paper we use the two "transverse" regions shown in Fig. 4 to define several types of MAX and MIN "transverse" regions. In Section III, MAX (MIN) refer to the "transverse" region containing largest (smallest) number of charged particles or to the region containing the largest (smallest) scalar p_T sum of charged particles. In Section IV, MAX and MIN refer to which of the two "transverse" regions contain the highest p_T charged particle, PTmaxT. 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 PTmaxT (*not including PTmaxT*). 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, $dN_{chg}/d\eta d\phi$, corresponds the number of charged particles per unit η-ϕ and the PT_{sum} density, $dPT_{sum}/d\eta d\phi$, corresponds the amount of charged scalar p_T sum per unit η-ϕ.

II. Data Selection and Monte-Carlo Generation

(1) Data Selection

The data used in this analysis arise from a sample of Stntuples created for the QCD group by Anwar Bhatti (see Table 1). This is the same data sample we used in our previous Run 2 analysis [5]. Events are required to be on the "goodrun" list. They are also required to have a missing E_T significance less than 5 $GeV^{1/2}$ and to have a sumET < 1.5 TeV. In addition, to be consistent with our Run 1 analysis only events with zero or one vertex with |z| < 60 cm are considered.

Table 1. Data sets and event selection criterion used in this analysis.

Event Selection	Min-Bias	JET20	JET50	JET70	JET100
Total Events	3,716,068	7,388,639	1,844,407	826,597	1,052,530
"Good" Events	3,094,114	5,185,515	1,397,771	642,289	822,466
MetSig < 5 $GeV^{1/2}$, sumET < 1.5 TeV	3,093,888	5,177,984	1,370,267	607,794	690,239
0 or 1 ZVtx, $\lvert z\rvert < 60$ cm	2,596,553	3,127,001	802,003	352,820	393,118
JetClu ($\lvert\eta(\text{jet})\rvert < 2$, R = 0.7)	587,154	2,473,013	735,893	338,668	389,006

As in our Run 1 analysis [2] we consider charged particles only in the region $p_T > 0.5$ GeV/c and $|\eta| < 1$ where the COT efficiency is high and compare uncorrected data with PYTHIA Tune A and HERWIG after CDFSIM. Our track selection criterion shown in Table 2 is the same as our Run 1 analysis. Systematic errors are calculated in the same way as in our published Run 1 analysis. We generate every plot twice, once with the track selection shown in Table 2 and again with the tighter cut $|d_0| < 0.5$ cm. 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.

Table 2. Track Selection criterion.

Track Selection
COT measured tracks
$\lvert z-z_0\rvert < 2$ cm
$\lvert d_0\rvert < 1$ cm
$p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$

In forming the observables presented in this analysis the five trigger sets shown in Table 1 are pieced together as shown in Table 3. The "looser" trigger set is used until it overlaps the next trigger set and then that trigger set is used until it overlaps the next trigger set etc..

Table 3. Range of ET(jet#1) used for each data set.

Trigger Set	Calorimeter Jets
Min-Bias	E_T(jet#1) < 30 GeV
JET20	30 < E_T(jet#1) < 70 GeV
JET50	70 < E_T(jet#1) < 95 GeV
JET70	95 < E_T(jet#1) < 130 GeV
JET100	E_T(jet#1) > 130 GeV

It is instructive to compare the "underlying event" (*i.e.* the "transverse" region) in a "hard scattering" process with an average "min-bias" collision. Table 4 shows the average number of charged particles, Nchg, the average scalar p_T sum of charged particles, PTsum, and the average maximum p_T charged particle, PTmax, for "min-bias" collisions at 1.96 TeV for the range p_T > 0.5 GeV/c and $|\eta| < 1$. In "min-bias" collisions at 1.96 TeV there are, on the average, about 3.2 charged particles with p_T > 0.5 GeV/c and $|\eta| < 1$. Dividing by 4π gives a charge density, $dNchg/d\eta d\phi$, of about 0.25 for an average "min-bias" collision at 1.96 TeV. Similarly, the average PTsum density, $dPTsum/d\eta d\phi$, is about 0.24 GeV/c for "min-bias" collisions at this energy. If there are no particles in the region p_T > 0.5 GeV/c and $|\eta| < 1$, then we set PTmax equal to zero when computing the average.

Table 4. Average number of charged particles, average PTsum, and average PTmax for "min-bias" collisions at 1.96 TeV for the range p_T > 0.5 GeV/c and $|\eta| < 1$. Also shown is the average charge density, $dNchg/d\eta d\phi$, and the average PTsum density, $dPTsum/d\eta d\phi$ (*i.e.* average divided by 4π).

	Observable	**Average**	**Average Density per unit η-ϕ**
Nchg	Number of Charged Particles (p_T > 0.5 GeV/c, $\|\eta\| < 1$)	3.17 ± 0.31	0.252 ± 0.025
PTsum (GeV/c)	Scalar p_T sum of Charged Particles (p_T > 0.5 GeV/c, $\|\eta\| < 1$)	2.97 ± 0.23	0.236 ± 0.018
PTmax (GeV/c)	Maximum p_T Charged Particle (p_T > 0.5 GeV/c, $\|\eta\| < 1$)	1.04 ± 0.04	

(2) Monte-Carlo Generation

In this analysis the data are compared with PYTHIA Tune A [6] and HERWIG at 1.96 TeV after detector simulation (*i.e.* CDFSIM). PYTHIA Tune A (4.9.1) was generated with the minimum P_T(hard) values shown in Table 5 and the Stntuples were created by Charles Currat and Dmitri Tsybych. HERWIG (4.10.4e) was generated with the minimum P_T(hard) values shown in Table 5 and we created the Stntuples.

Table 5. PYTHIA Tune A (4.9.1) at 1.96 TeV.

P_T(hard) minimum	**Events**
0 GeV/c	500,000
5 GeV/c	497,500
10 GeV/c	497,500
18 GeV/c	927,000
40 GeV/c	331,500
60 GeV/c	338,000
90 GeV/c	271,900
125 GeV/c	578,202
Total	3,941,602

Table 6. HERWIG (4.10.4e) at 1.96 TeV.

P_T(hard) minimum	Events
5 GeV/c	490,999
15 GeV/c	509,641
18 GeV/c	508,129
40 GeV/c	485,000
50 GeV/c	487,499
90 GeV/c	484,995
125 GeV/c	488,123
Total	3,421,386

To be consistent with our previous analysis [5] the calorimeter jet energy scale has been shifted by a scale factor of 1.042. However, none of the results presented here are sensitive to a jet energy scale shift of this size. Smooth curves have been drawn through the Monte-Carlo predictions to aid in comparing the theory with the data.

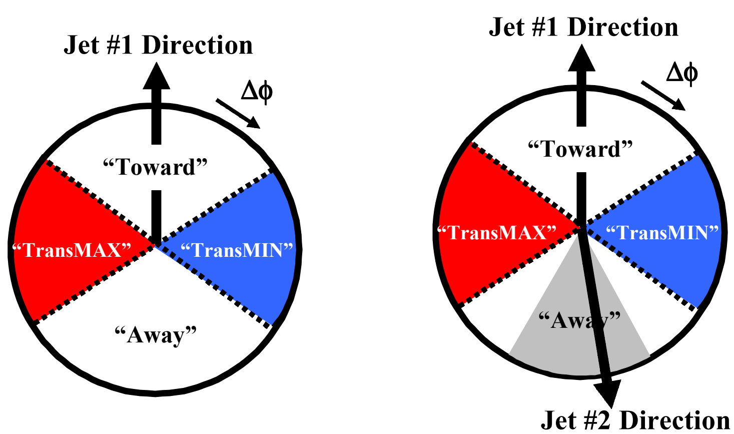


Fig. 5. Illustration of correlations in azimuthal angle $\Delta\phi$ relative to the direction of the leading jet (highest E_T jet) in the event, jet#1 for "leading jet" events (*left*) and "back-to-back" events (*right*) as defined in Fig. 4. The angle $\Delta\phi = \phi - \phi_{jet\#1}$ is the relative 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, $60^o < \Delta\phi < 120^o$ and $60^o < -\Delta\phi < 120^o$. "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.

III. MAX and MIN "Transverse" Regions

(1) Definition

As shown in Fig. 5 we use the direction of the highest E_T jet in the region $|\eta| < 2$, jet#1, to define the two "transverse" regions, $60^o < \Delta\phi < 120^o$ and $60^o < -\Delta\phi < 120^o$. On an event-by-event basis, we define "transMAX" and "transMIN" to be the maximum and minimum of these two regions. "TransMAX" and "transMIN" each have an area in η-ϕ space of $\Delta\eta\Delta\phi = 4\pi/6$. When looking at multiplicities MAX and MIN refer to the number of charged particles, however, when we consider the PTsum then MAX and MIN refer to the scalar p_T sum of charged particles. In our previous Run 2 analysis [5] we examined the densities in the overall "transverse" region which correspond to the average of "transMAX" and "transMIN" densities.

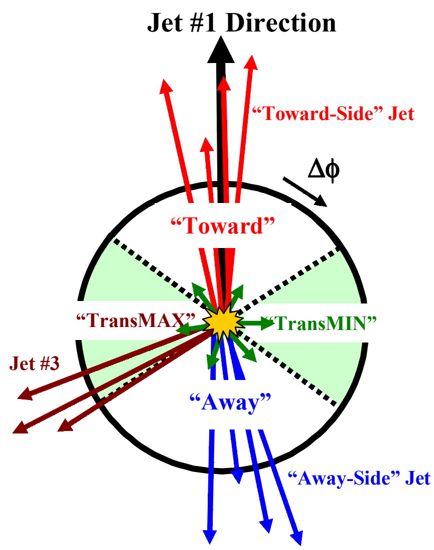


Fig. 6. Illustration of the topology of a proton-antiproton collision in which a "hard" parton-parton collision has occurred. The "toward" region as defined in Fig. 3 contains the leading "jet", while the "away" region, on the average, contains the "away-side" "jet". The "transverse" region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the "underlying event". For events with large initial or final-state radiation the "transMAX" region defined in Fig.5 would contain the third jet while both the "transMAX" and "transMIN" regions receive contributions from the beam-beam remnants (see Fig. 1). Thus the "transMIN" region is very sensitive to the beam-beam remnants, while the "transMAX" minus the "transMIN" is very sensitive to initial and final-state radiation.

As illustrated in Fig. 6, one expects that "transMAX" will pick up the hardest initial or final-state radiation while both "transMAX" and "transMIN" should receive "beam-beam remnant" contributions. Hence one expects "transMIN" to be more sensitive to the "beam-beam remnant" component of the "underlying event" and the difference between "transMAX" and "transMIN" should be very sensitive to the "hard scattering" component of the "underlying event". This idea, was first suggested by Bryan Webber, and implemented in a paper by Jon Pumplin [8]. Also, Valaria Tano [9] studied this in her Run 1 analysis of maximum and minimum transverse cones (R = 0.7).

(2) "Leading Jet" Events

Fig. 7 compares PYTHIA Tune A (after CDFSIM) with the data on the average density of charged particles, dNchg/dηdϕ, and the average PTsum density, dPTsum/dηdϕ, in the "transMAX" and "transMIN" regions for "leading jet" events (defined in Fig. 5) as a function of the leading jet E_T. Also shown are the average of "transverse" densities (*i.e.* average of "transMAX" and "transMIN"). Fig. 8 shows the same data compared with HERWIG (after CDFSIM). HERWIG does not include multiple parton interactions and for E_T(jet#1) less that about 150 GeV lies below the data. This is exactly what we found in our published Run 1 analysis [2]. It is interesting, however, that HERWIG agrees well for E_T(jet#1) > 150 GeV.

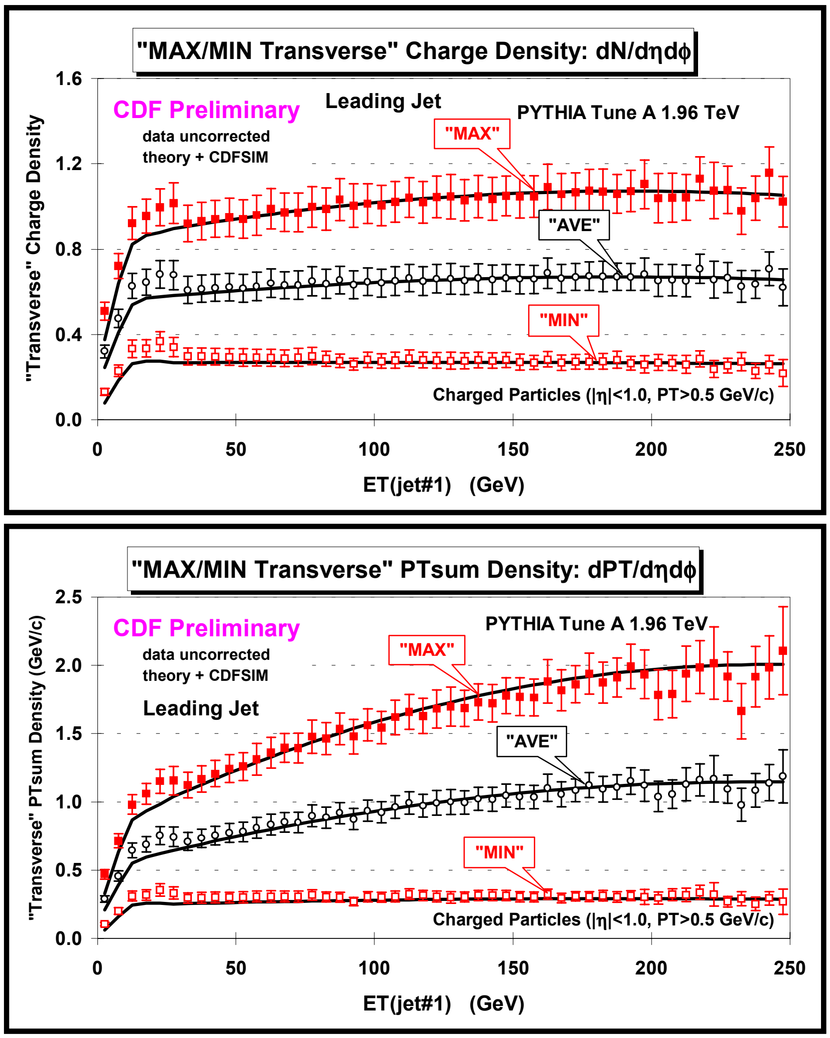


Fig. 7. Data on the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" and "transMIN" regions for "leading jet" events defined in Fig. 5 as a function of the leading jet E_T. Also shown is the average of "transMAX" and "transMIN" (*i.e.* the overall "transverse" density). The theory curves corresponds to PYTHIA Tune A at 1.96 TeV after CDFSIM.

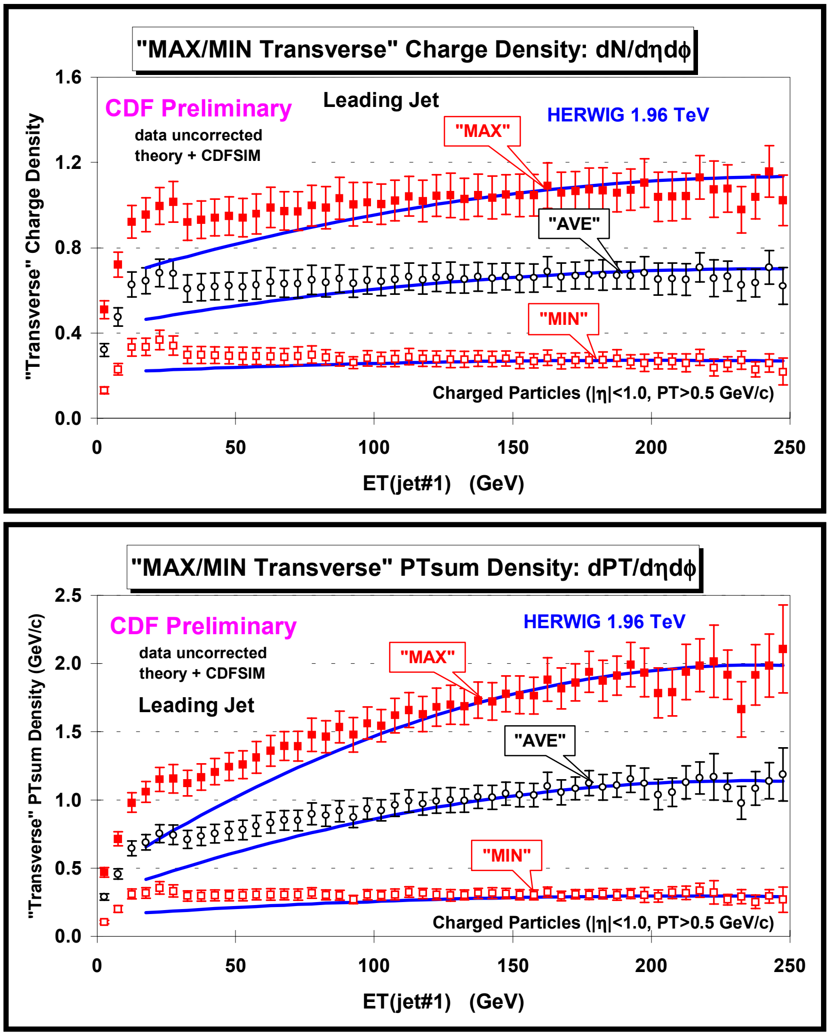


Fig. 8. Data on the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" and "transMIN" regions for "leading jet" events defined in Fig. 5 as a function of the leading jet E_T. Also shown is the average of "transMAX" and "transMIN" (*i.e.* the overall "transverse" density). The theory curves corresponds to HERWIG at 1.96 TeV after CDFSIM.

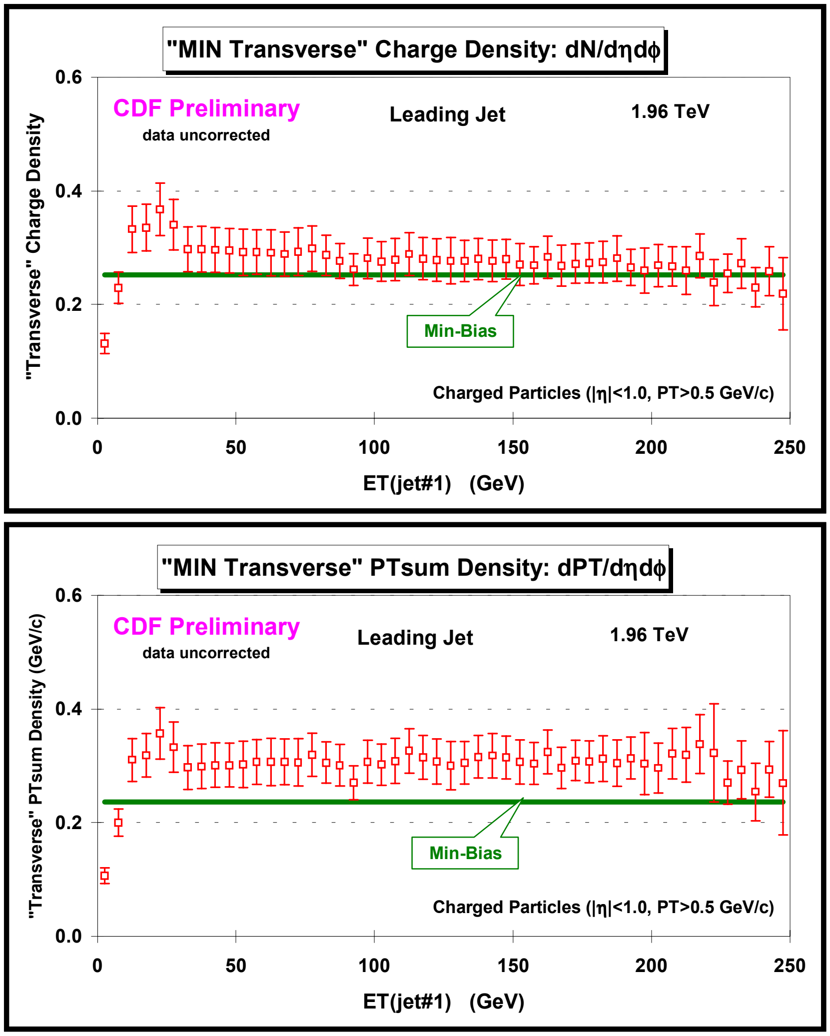


Fig. 9. Data on the average density of charged particles dNchg/dηdφ (*top*) and the average PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMIN" region for "leading jet" events defined in Fig. 5 as a function of the leading jet E_T. Also shown is the average density of charged particles dNchg/dηdφ (*top*) and the average PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "min-bias" collisions at 1.96 TeV (see Table 4).

Fig. 9 compares the "min-bias" densities from Table 4 with the data on the average density of charged particles, dNchg/dηdφ, and the average PTsum density, dPTsum/dηdφ, in the "transMIN" region for "leading jet" events (defined in Fig. 5) as a function of the leading jet E_T. The "transMIN" region contains less "hard scattering" than the "transMAX" region and the "transMIN" densities are very similar to what is observed for "min-bias" collisions.

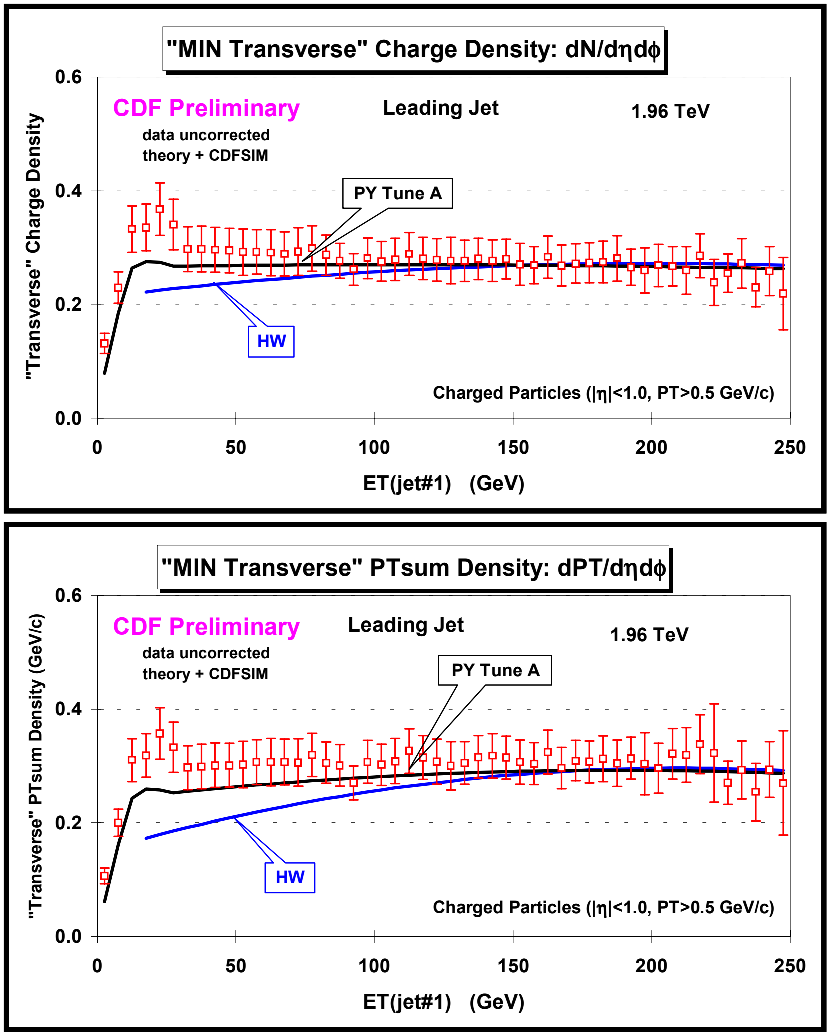
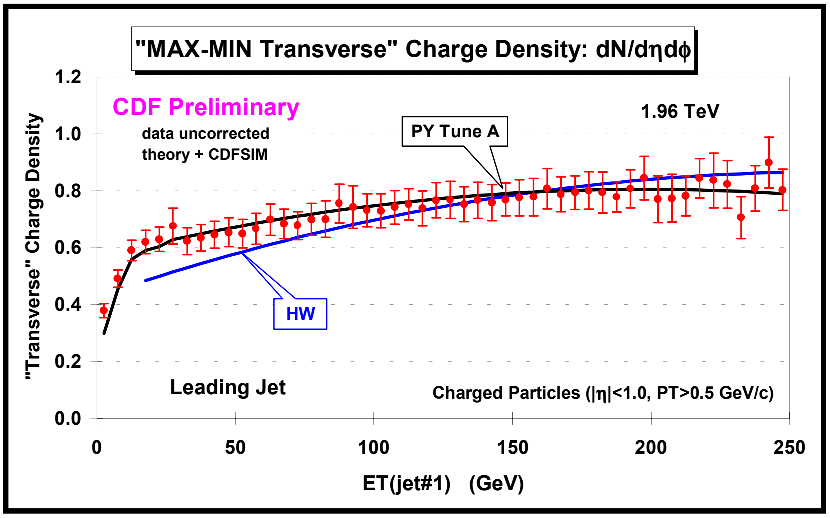


Fig. 10. Data on the average density of charged particles dNchg/dηdφ (*top*) and the average PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and |η| < 1 in the "transMIN" region for "leading jet" events defined in Fig. 5 as a function of the leading jet E_T compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

Fig. 10 compares PYTHIA Tune A and HERWIG with the data on the average density of charged particles, dNchg/dηdφ, and the average PTsum density, dPTsum/dηdφ, in the "transMIN" region for "leading jet" events (defined in Fig. 5) as a function of the leading jet E_T. The "transMIN" densities are more sensitive to the "beam-beam remnant" and multiple parton interaction components 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).



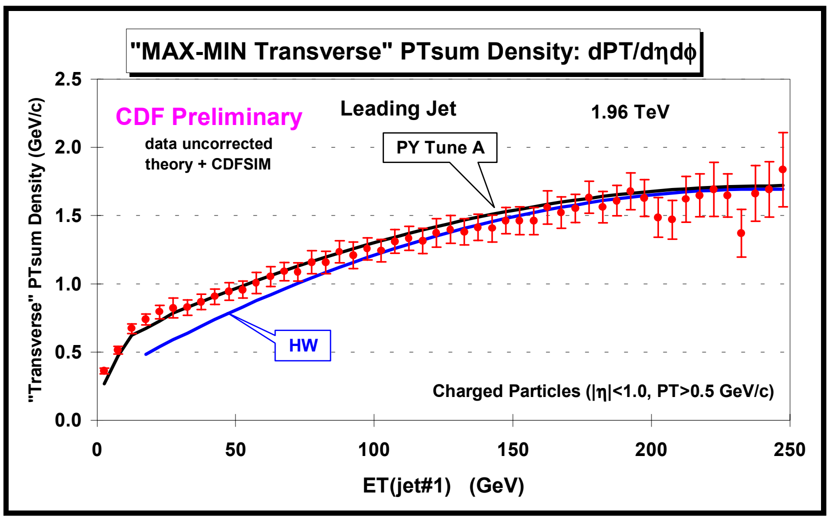


Fig. 11. Data on the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for the "transMAX" minus the "transMIN" region for "leading jet" events defined in Fig. 5 as a function of the leading jet E_T compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

Fig. 11 compares PYTHIA Tune A and HERWIG with the data on the average density of charged particles, dNchg/dηdϕ, and the average PTsum density, dPTsum/dηdϕ, for the "transMAX" minus the "transMIN" region (*i.e.* the difference) for "leading jet" events (defined in Fig. 5) as a function of the leading jet E_T. The difference between "transMAX" and "transMIN" is very sensitive to the "hard scattering" component of the "underlying event" (*i.e.* hard initial and final-state radiation). However, here again PYTHIA Tune A (with multiple parton interactions) does a better job describing the data than HERWIG (without multiple parton interactions).

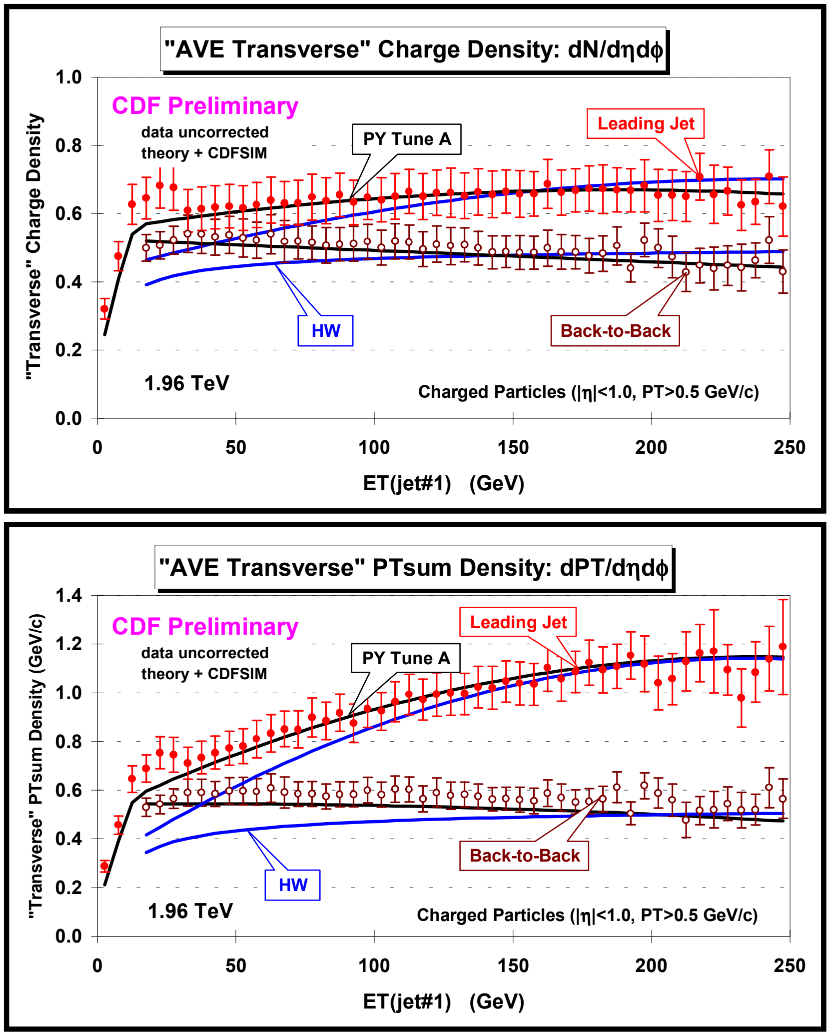


Fig. 12. Data on the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for the "transverse" region for "leading jet" events and for "back-to-back" events defined in Fig. 4 as a function 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.

(3) "Back-to-Back" Events

Fig. 12 compares the "leading jet" and "back-to-back" data on the average density of charged particles, dNchg/dηdϕ, and the average PTsum density, dPTsum/dηdϕ, in the "transverse" region (*i.e.* average of "transMAX" and "transMIN") as a function of the leading jet E_T. Fig.12 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 remnant" and multiple parton scattering component of the "underlying event" and PYTHIA Tune A (with multiple parton interactions) does a better job describing the data than HERWIG (without multiple parton interactions). 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.

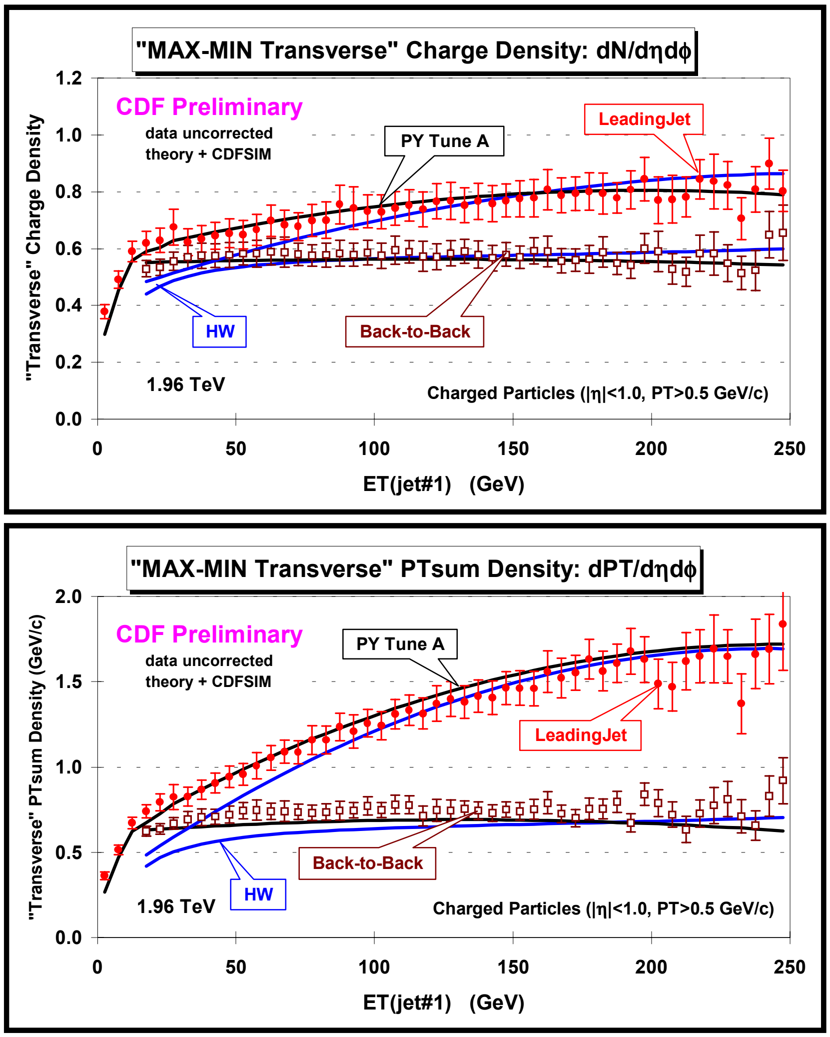
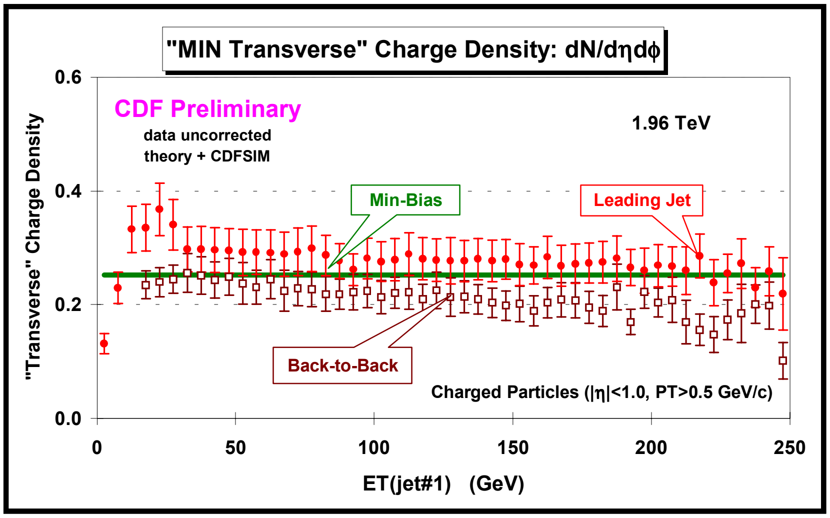


Fig. 13. Data on the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for the "transMAX" minus the "transMIN" region defined in Fig. 5 for "leading jet" events and for "back-to-back" 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.

Fig. 13 compares the "leading jet" and "back-to-back" data on the average density of charged particles, dNchg/dηdϕ, and the average PTsum density, dPTsum/dηdϕ, for the "transMAX" minus the "transMIN" region (*i.e.* the difference) as a function of the leading jet E_T. Fig.13 also shows the predictions of PYTHIA Tune A and HERWIG after CDFSIM. The difference between "transMAX" and "transMIN" is very sensitive to the "hard scattering" component of the "underlying event" (*i.e.* hard initial and final-state radiation) and therefore we expect to see a big difference between the "leading jet" events and the "back-to-back" events which is indeed the case. Again, PYTHIA Tune A does a better job describing the data than HERWIG.



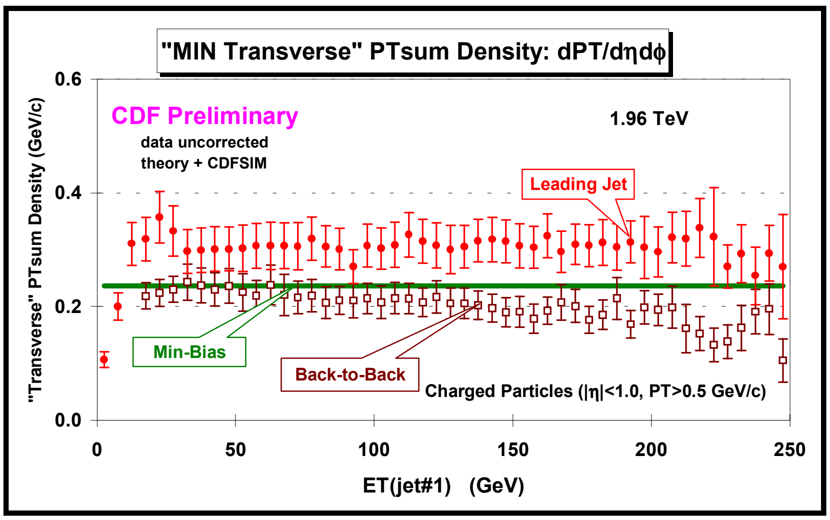


Fig. 14. Data on the average density of charged particles dNchg/dηdφ (*top*) and the average PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMIN" region defined in Fig. 5 for "leading jet" events and for "back-to-back" events defined in Fig. 4 as a function of the leading jet E_T. Also shown is the average density of charged particles dNchg/dηdφ (*top*) and the average PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "min-bias" collisions at 1.96 TeV (see Table 4).

Fig. 14 compares the "min-bias" densities from Table 4 with the "leading jet" and "back-to-back" data on the average density of charged particles, dNchg/dηdφ, and the average PTsum density, dPTsum/dηdφ, in the "transMIN" region as a function of the leading jet E_T. The "transMIN" densities are more sensitive to the "beam-beam remnant" and multiple parton interaction components of the "underlying event" and therefore we expect the "leading jet" and "back-to-back" events to be similar to each other and similar to what is observed for "min-bias" collisions which is what Fig. 14 shows.

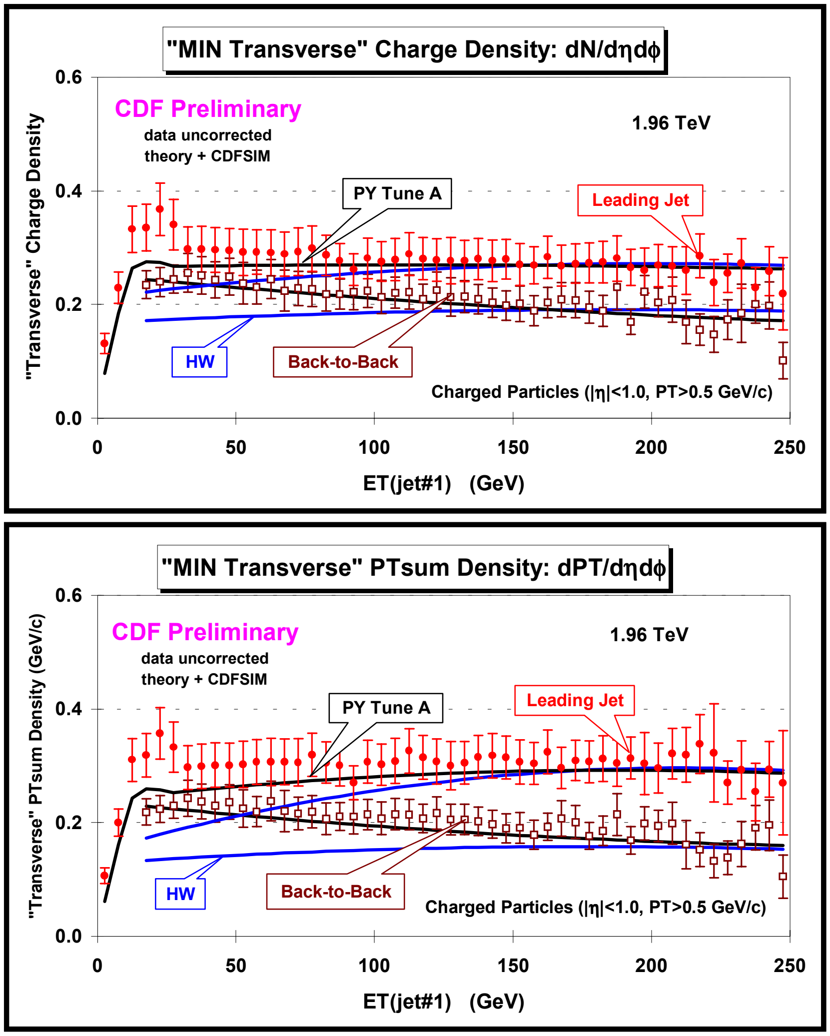
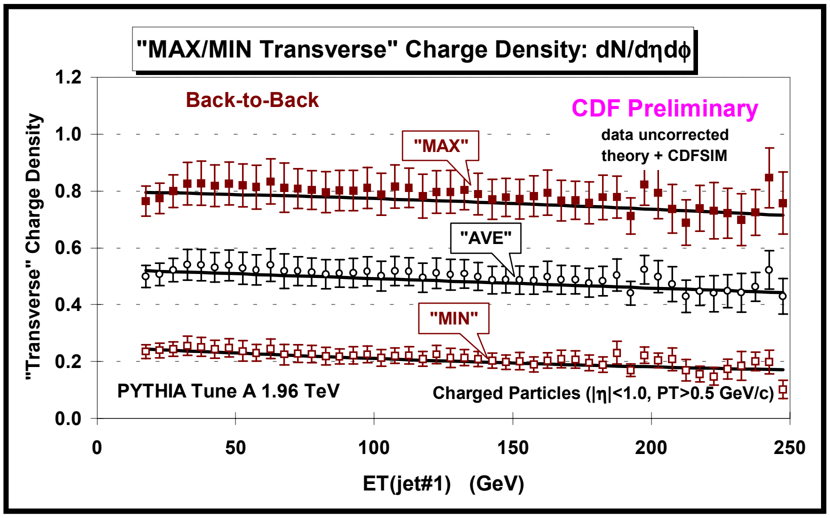


Fig. 15. Data on the average density of charged particles dNchg/dηdφ (*top*) and the average PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMIN" region defined in Fig. 5 for "leading jet" events and for "back-to-back" events defined in Fig. 4 as a function of the leading jet E_T compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

Fig. 15 compares PYTHIA Tune A and HERWIG with the "leading jet" and "back-to-back" data on the average density of charged particles, dNchg/dηdφ, and the average PTsum density, dPTsum/dηdφ, in the "transMIN" region as a function of the leading jet E_T. 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 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).



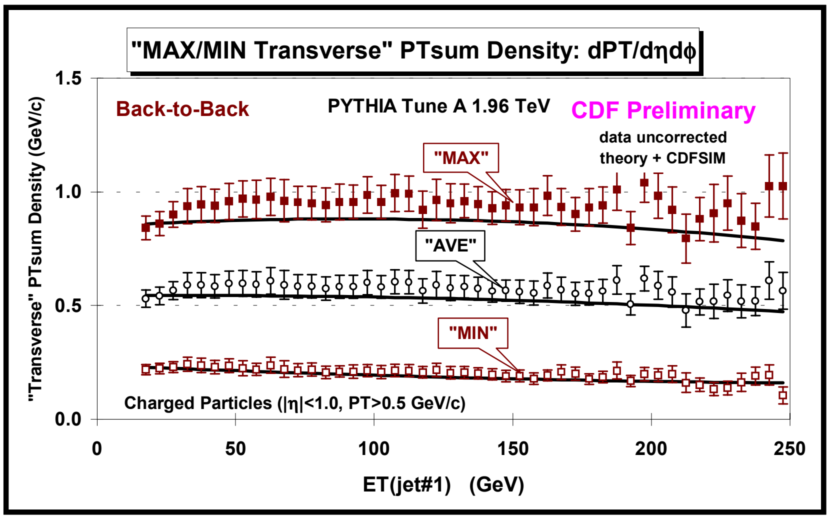


Fig. 16. Data on the average density of charged particles $dN_{chg}/d\eta d\phi$ (*top*) and the average PTsum density $dPT_{sum}/d\eta d\phi$ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" and "transMIN" regions defined in Fig. 5 for "back-to-back" events defined in Fig. 4 as a function of the leading jet E_T. Also shown is the average of "transMAX" and "transMIN" (*i.e.* the overall "transverse" density). The theory curves correspond to PYTHIA Tune A at 1.96 TeV after CDFSIM.

Fig. 16 and Fig. 17 compare PYTHIA Tune A and HERWIG, respectively, to the data on the average density of charged particles, $dN_{chg}/d\eta d\phi$, and the average PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transMAX" and "transMIN" regions for "back-to-back" events (defined in Fig. 5) as a function of the leading jet E_T.

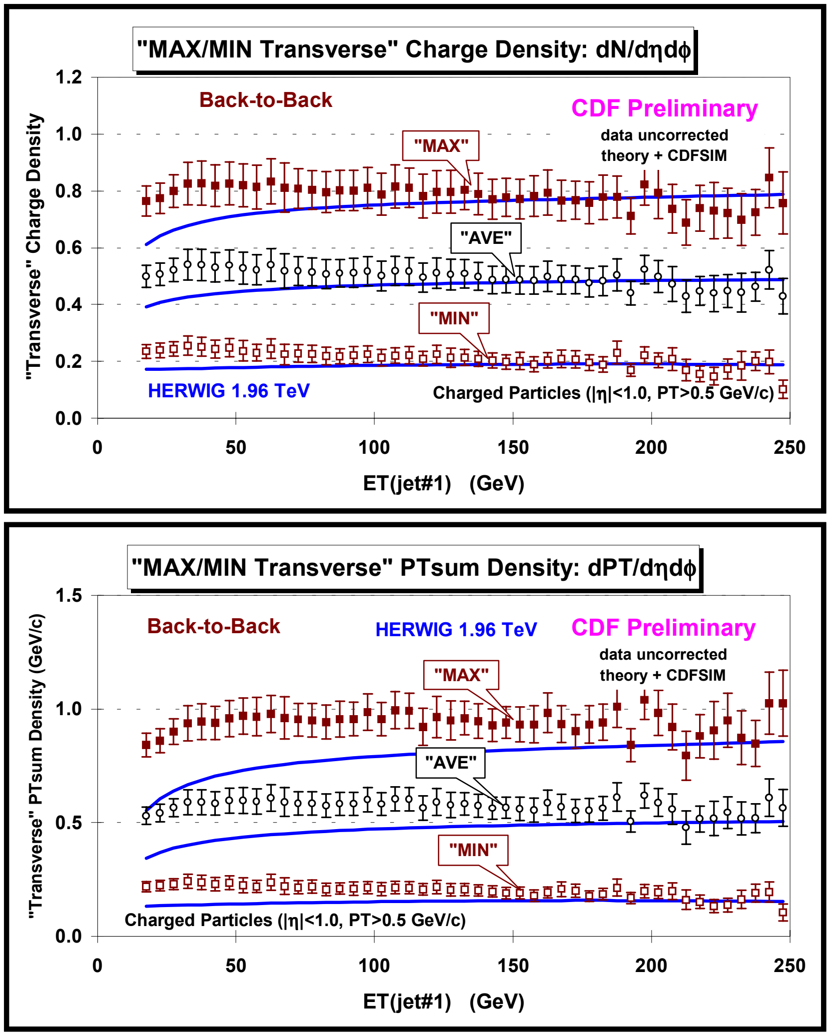


Fig. 17. Data on the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" and "transMIN" regions defined in Fig. 5 for "back-to-back" events defined in Fig. 4 as a function of the leading jet E_T. Also shown is the average of "transMAX" and "transMIN" (*i.e.* the overall "transverse" density). The theory curves correspond to HERWIG at 1.96 TeV after CDFSIM.

IV. "Associated" Transverse Densities

(1) Definition

Here we will define a different "MAX" and "MIN" transverse region. In this case "MAX" and "MIN" refer to which of the two "transverse" regions contain the highest p_T charged particle. As shown in Fig. 18 we use the direction of the highest E_T jet in the region $|\eta| < 2$, jet#1, to define the two "transverse" regions, $60^o < \Delta\phi < 120^o$ and $60^o < -\Delta\phi < 120^o$. The highest p_T charged particle in the "transverse" region, PTmaxT, is used, on an event by event basis, to define the "transMAX" and "transMIN" regions. The "transMAX" region is the region that contained PTmaxT and "transMIN" is the other "transverse" region. As before the "transMAX" and "transMIN" each have an area in η-ϕ space of $\Delta\eta\Delta\phi = 4\pi/6$, but now we study the densities in these two regions excluding PTmaxT. We refer to these as "associated" densities since they correspond to the density of charged particles that are associated with PTmaxT (not including PTmaxT). The "associated" densities are a measure of the correlations between the particles in the "transverse" region. Large "transMAX" associated densities indicate "jet" structure" in the "transverse" region and the "transMIN" associated densities are a measure of the correlations between the two "transverse" regions.

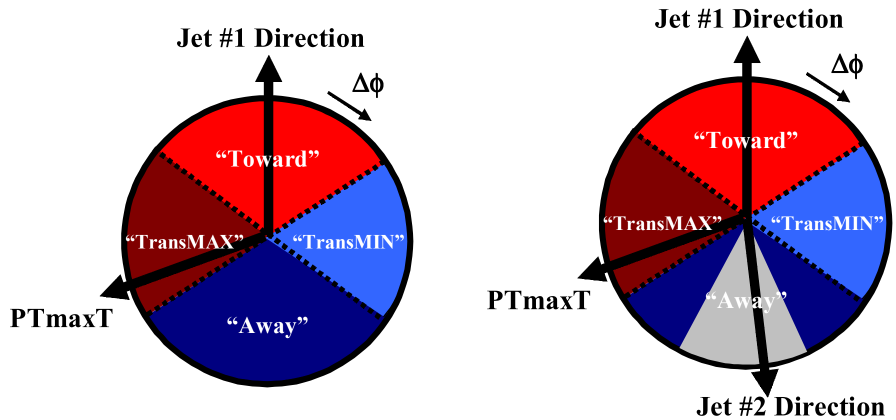


Fig. 18. Illustration of correlations in azimuthal angle Δϕ relative to the direction of the leading jet (highest E_T jet) in the event, jet#1 for "leading jet" events (*left*) and "back-to-back" events (*right*) as defined in Fig. 4. The angle $\Delta\phi = \phi - \phi_{jet\#1}$ is the relative azimuthal angle between charged particles and the direction of jet#1. The highest p_T charged particle in the "transverse" region, PTmaxT, is used, on an event by event basis, to define the "transMAX" and "transMIN" regions. The "transMAX" region contains PTmaxT and "transMIN" is the other "transverse" region. To examine jet structure in the "underlying event" we define "associated" charged particle densities that measure the number of charged particles and the scalar p_T sum of charged particles accompanying PTmaxT (*not including PTmaxT*).

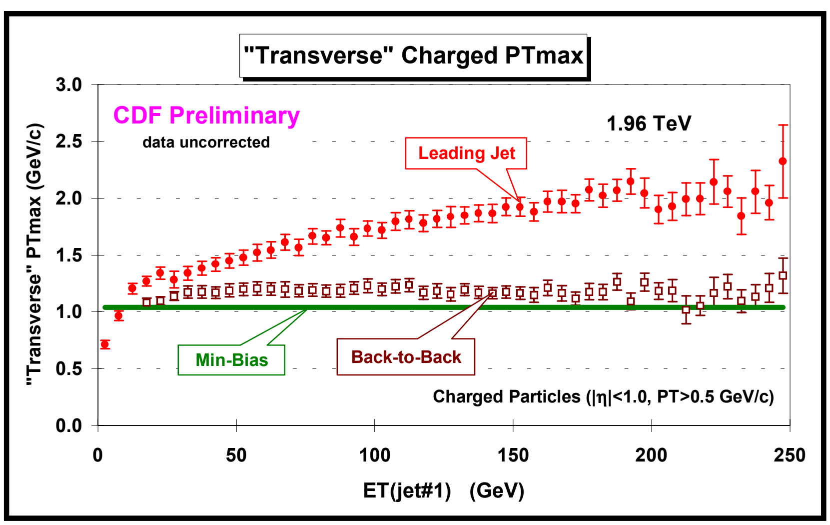


Fig. 19. Data on the average maximum transverse momentum charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the "transverse" region, PTmaxT, for "leading jet" events and for "back-to-back" events defined in Fig. 5 as a function of the leading jet E_T. Also shown is the average maximum transverse momentum charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$), PTmax, for "min-bias" collisions at 1.96 TeV (see Table 4). If there are no particles in the region $p_T > 0.5$ GeV/c and $|\eta| < 1$, then we set PTmax equal to zero when computing the average.

(2) "Transverse" PTmax

Fig. 19 compares the average maximum p_T charged particle, PTmax, in "min-bias" collisions from Table 4 with the "leading jet" and "back-to-back" data on the average maximum p_T charged particle in the "transverse" region, PTmaxT, as a function of the leading jet E_T. The average PTmaxT increases with E_T(jet#1) for the "leading jet" events and for the "back-to-back" events it is flat and almost equal to the average PTmax for "min-bias" collisions. As expected the "back-to-back" topology suppresses hard initial and final-state radiation.

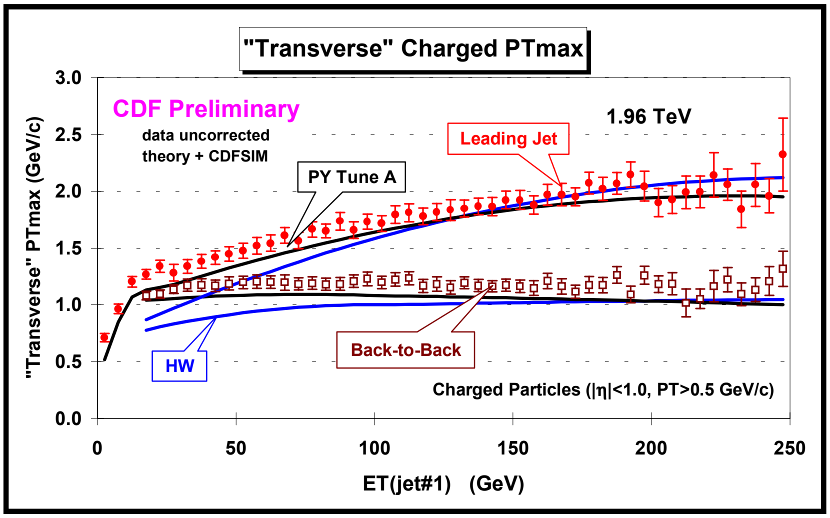


Fig. 20. Data from Fig. 19 on the average maximum transverse momentum charged particle (p_T > 0.5 GeV/c, |η| < 1) in the "transverse" region, PTmaxT, for "leading jet" events and for "back-to-back" events defined in Fig. 5 as a function of the leading jet E_T compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

Fig. 20 compares PYTHIA Tune A and HERWIG with the "leading jet" and "back-to-back" data on the average maximum p_T charged particle in the "transverse" region, PTmaxT, as a function of the leading jet E_T.

Fig. 21 compares the p_T distribution of the maximum p_T charged particle, PTmax, in "min-bias" collisions with the "leading jet" and "back-to-back" data on the p_T distribution of the maximum p_T charged particle in the "transverse" region, PTmaxT, with 30 < E_T(jet#1) < 70 GeV. Although the "back-to-back" topology suppresses hard initial and final-state radiation, the "back-to-back" events are "harder" than "min-bias" events, but not nearly as "hard" as the "leading jet" events. We will see that finding a high p_T particle indicates the presence of a "jet", so in Fig. 21 one is in a sense comparing the probability of finding a third jet in the "transverse" region of a "hard scattering" process to the probability of finding a single jet in "min-bias" collisions. As we have seen many times before [2,5] the "underlying event" (*i.e.* "transverse" region) in a hard scattering process is more active than an average "min-bias" collision. It has a higher density of charged particles, a larger PTsum density, and a larger PTmax than an average "min-bias" collision.

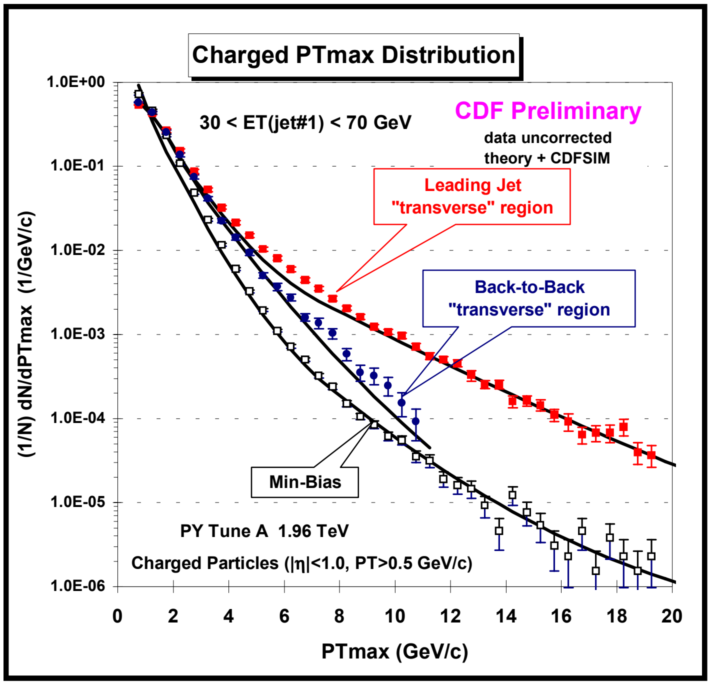


Fig. 21. Data on the transverse momentum distribution of the charged particle ($|\eta| < 1$) with the highest p_T in the "transverse" region, PTmaxT, for "leading jet" and "back-to-back" events define in Fig. 5 with $30 < E_T(\text{jet\#1}) < 70$ GeV. Also shown is the transverse momentum distribution of the charged particle ($|\eta| < 1$) with the highest p_T, PTmax, in "min-bias" collisions at 1.96 TeV. The points correspond to (1/N) dN/dPTmax normalized to one. The data are compared with PYTHIA Tune A (after CDFSIM).

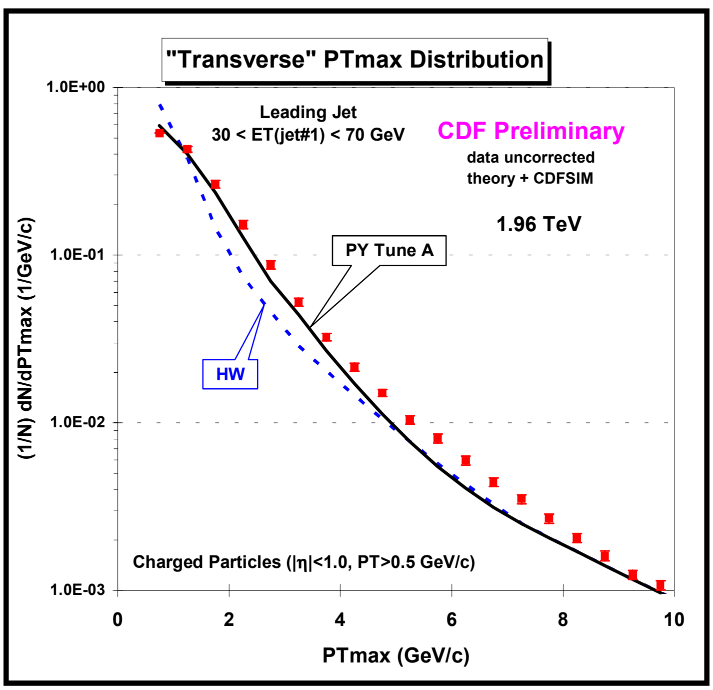


Fig. 22. Data from Fig. 21 on the transverse momentum distribution of the charged particle ($|\eta| < 1$) with the highest p_T in the "transverse" region, PTmaxT, for "leading jet" events define in Fig. 5 with $30 < E_T(\text{jet\#1}) < 70$ GeV compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

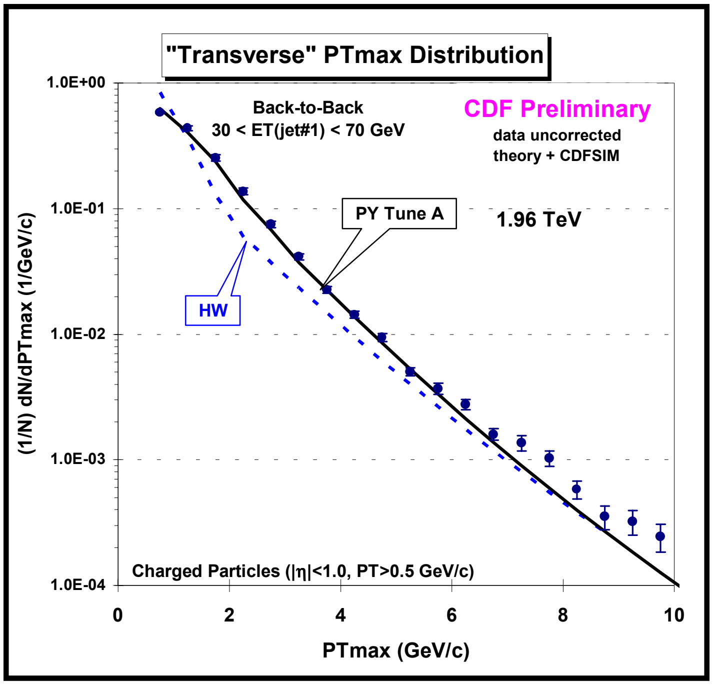


Fig. 23. Data from Fig. 21 on the transverse momentum distribution of the charged particle ($|\eta| < 1$) with the highest p_T in the "transverse" region, PTmaxT, for "back-to-back" events define in Fig. 5 with $30 < E_T$(jet#1) < 70 GeV compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

Fig. 22 and Fig 23 compare the "leading jet" and "back-to-back" data, respectively, on the p_T distribution of the maximum p_T charged particle in the "transverse" region, PTmaxT, with $30 < E_T$(jet#1) < 70 GeV with PYTHIA Tune A and HERWIG after CDFSIM. Although PYTHIA Tune A (with multiple parton interactions) does not fit the data perfectly it does a much better job than HERWIG (without multiple parton interactions). HERWIG produces a PTmax distribution that is much too steep at low values of PTmaxT.

(3) "Leading Jet" Events

Fig. 24 shows the data on the average "associated" density of charged particles, $dN_{chg}/d\eta d\phi$, and the average "associated" PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transMAX" (*not including PTmaxT*) and "transMIN" regions for "leading jet" events (defined in Fig. 5) as a function of the leading jet E_T. Also shown are the average "transverse" densities for "leading jet" events from Fig. 7. The data show large correlations in the "transverse" region suggesting that PTmaxT comes from a "jet". For E_T(jet#1) greater than about 50 GeV there is a higher density of charged particles "associated" with PTmaxT in the "transMAX" region than there is in the average "transverse" region. Note that one particle in the "transMAX" region corresponds to a density of $6/4\pi$ or about 0.5 and the average value of PTmaxT is around 1.4 GeV/c (see Fig. 24). These correlations indicate "jet" structure in the "underlying event" (*i.e.* "transverse" region) even at fairly low p_T.

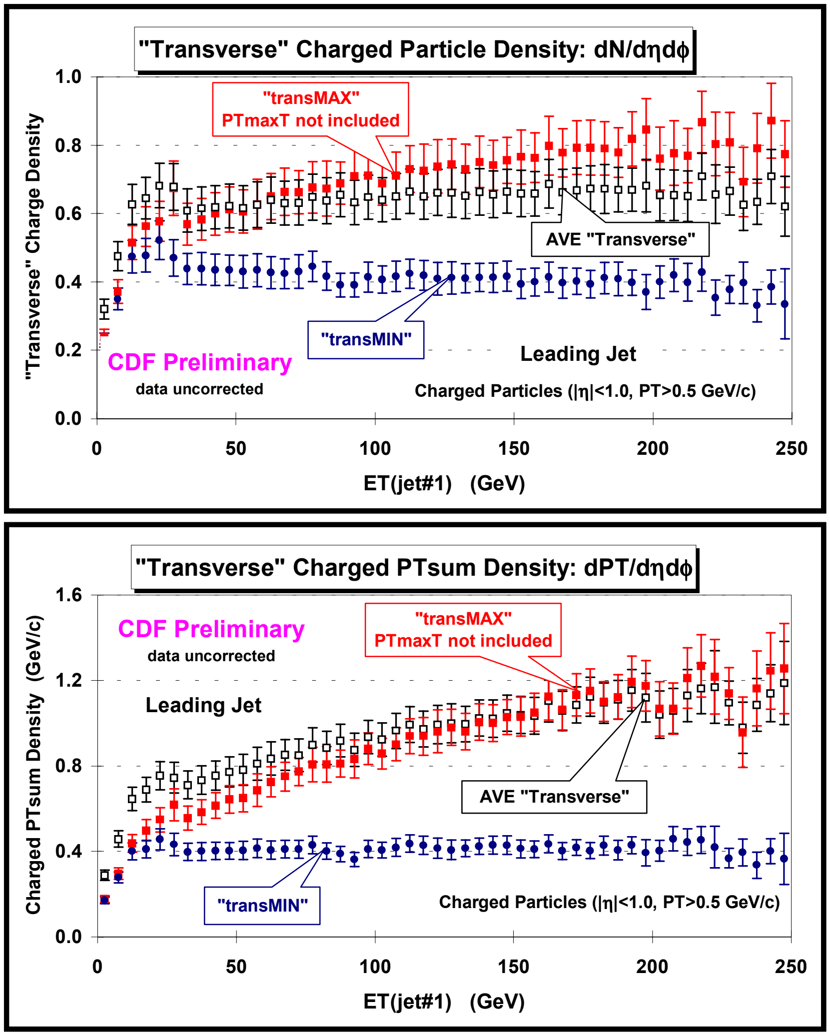
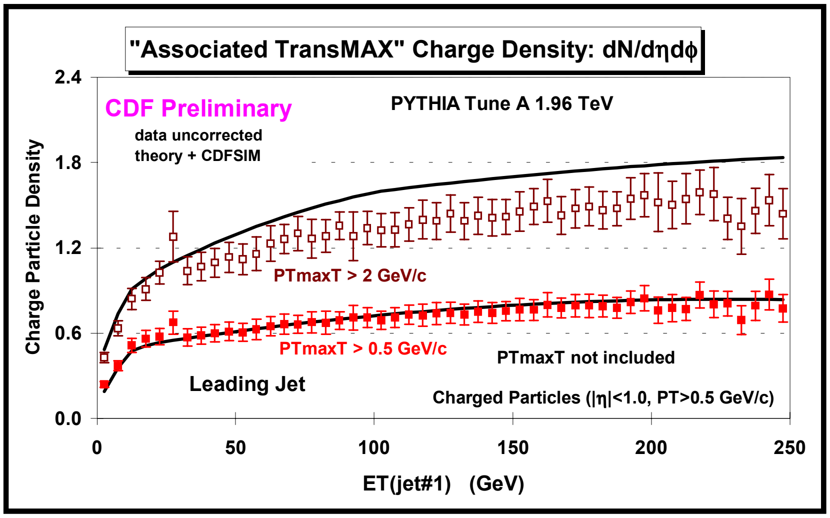


Fig. 24. Data on the average "associated" density of charged particles dNchg/dηdϕ (*top*) and the average "associated" PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and |η| < 1 in the "transMAX" (*not including PTmaxT*) and "transMIN" regions defined in Fig. 18 for "leading jet" events defined in Fig. 4 as a function of the leading jet E_T. Also shown is the average density of charged particles dNchg/dηdϕ (*top*) and the average PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and |η| < 1 in the "transverse" region for "leading jet" events defined in Fig. 5.



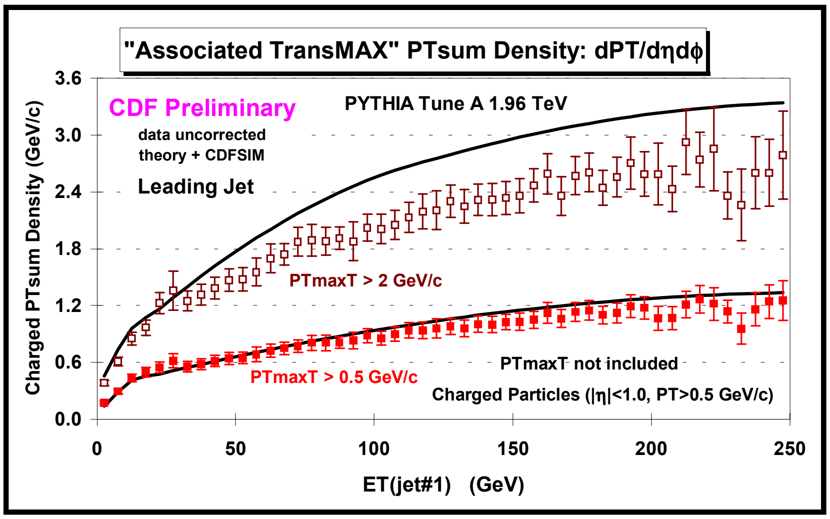
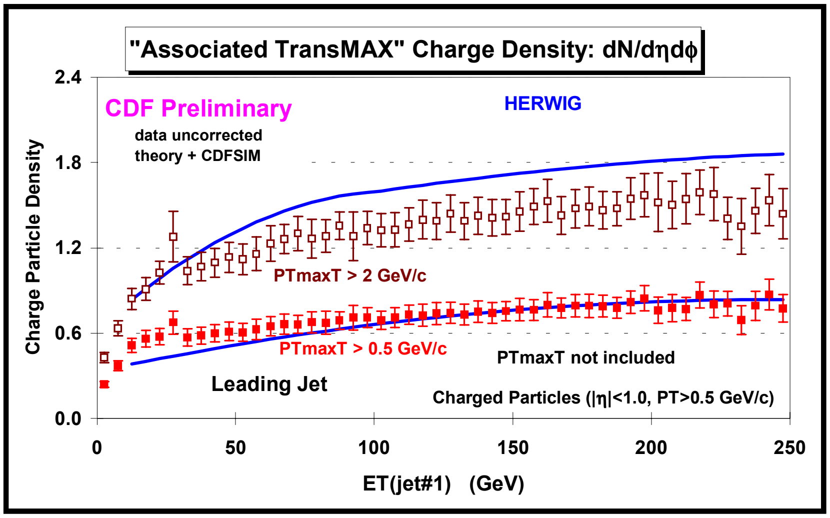


Fig. 25. Data on the average "associated" density of charged particles $dN_{chg}/d\eta d\phi$ (*top*) and the average "associated" PTsum density $dPT_{sum}/d\eta d\phi$ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" (*not including PTmaxT*) region defined in Fig. 18 for "leading jet" events defined in Fig. 4 with PTmaxT > 0.5 GeV/c and PTmaxT > 2.0 GeV/c as a function of the leading jet E_T. The theory curves correspond to PYTHIA Tune A at 1.96 TeV after CDFSIM.



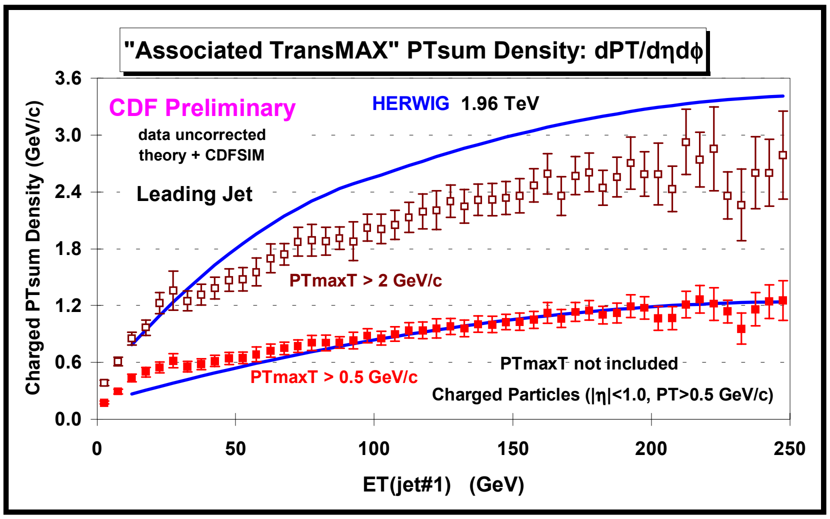
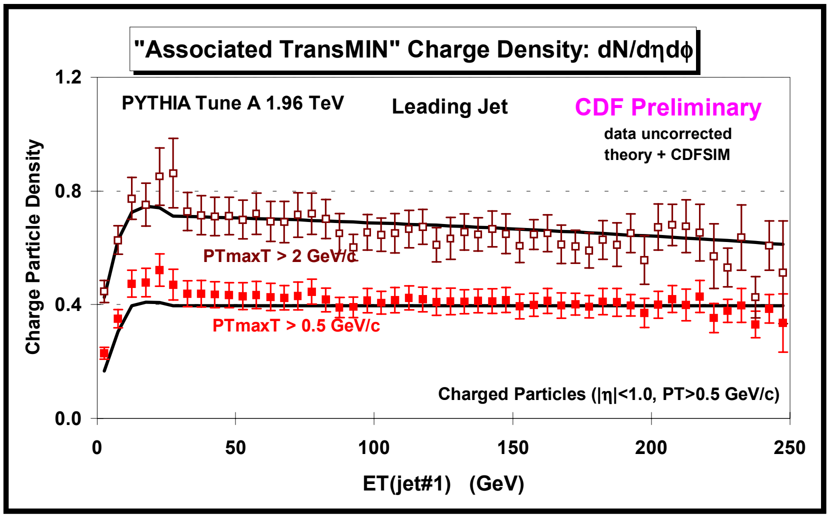


Fig. 26. Data on the average "associated" density of charged particles dNchg/dηdϕ (*top*) and the average "associated" PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMAX" (*not including PTmaxT*) region defined in Fig. 18 for "leading jet" events defined in Fig. 4 with PTmaxT > 0.5 GeV/c and PTmaxT > 2.0 GeV/c as a function of the leading jet E_T. The theory curves correspond to HERWIG at 1.96 TeV after CDFSIM.

Fig. 25 and Fig. 26 compare PYTHIA Tune A and HERWIG, respectively, with data on the average "associated" density of charged particles, dNchg/dηdϕ, and the average PTsum "associated" density, dPTsum/dηdϕ, in the "transMAX" (*not including PTmaxT*) region for "leading jet" events (defined in Fig. 5) with PTmaxT > 0.5 GeV/c and PTmaxT > 2.0 GeV/c as a function of the leading jet E_T. For larger values of PTmaxT the correlations are even stronger. It is interesting that both PYTHIA Tune A and HERWIG predict a slightly larger correlation for PTmaxT > 2.0 GeV than is seen in the data.



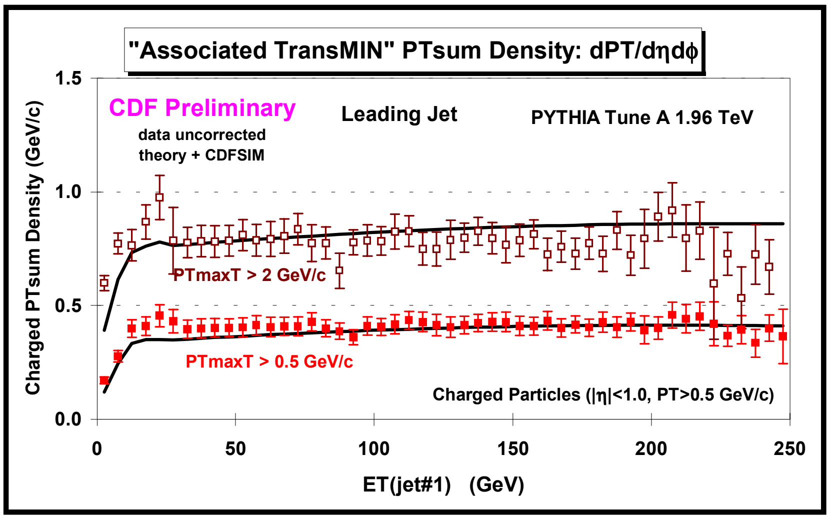


Fig. 27. Data on the average "associated" density of charged particles dNchg/dηdφ (*top*) and the average "associated" PTsum density dPTsum/dηdφ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMIN" region defined in Fig. 18 for "leading jet" events defined in Fig. 4 with PTmaxT > 0.5 GeV/c and PTmaxT > 2.0 GeV/c as a function of the leading jet E_T. The theory curves correspond to PYTHIA Tune A at 1.96 TeV after CDFSIM.

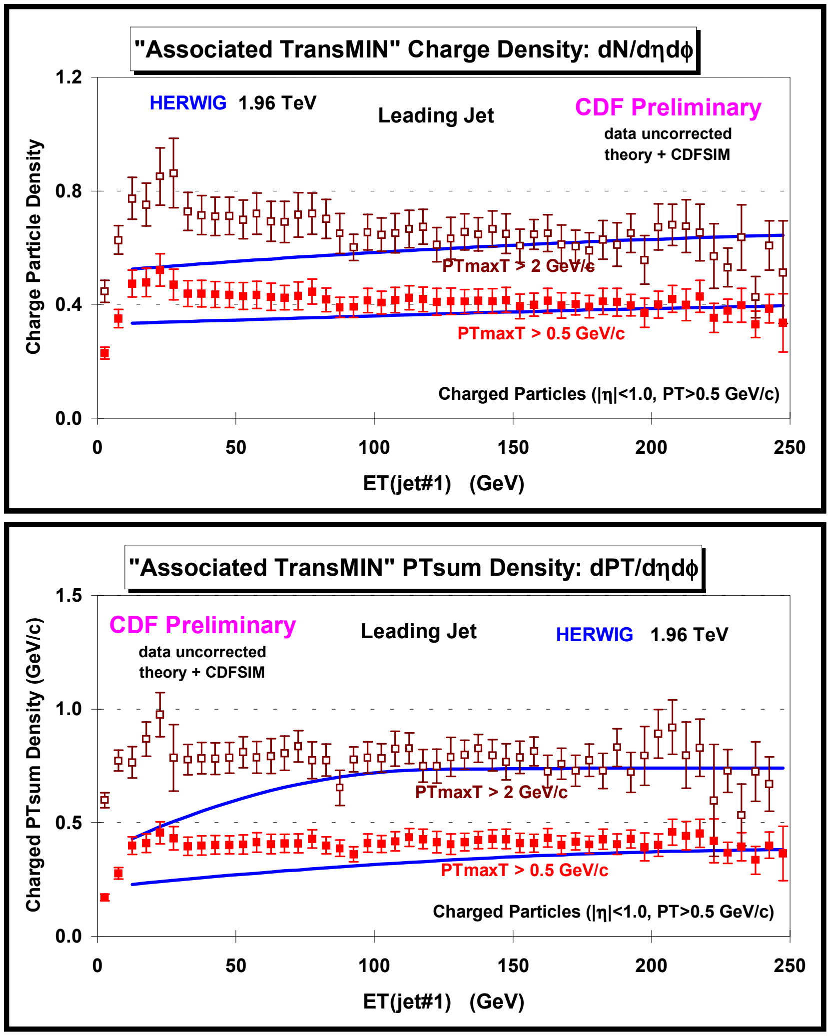


Fig. 28. Data on the average "associated" density of charged particles dNchg/dηdϕ (*top*) and the average "associated" PTsum density dPTsum/dηdϕ (*bottom*) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transMIN" region defined in Fig. 18 for "leading jet" events defined in Fig. 4 with PTmaxT > 0.5 GeV/c and PTmaxT > 2.0 GeV/c as a function of the leading jet E_T. The theory curves correspond to HERWIG at 1.96 TeV after CDFSIM.

Fig. 27 and Fig. 28 compare PYTHIA Tune A and HERWIG, respectively, with data on the average "associated" density of charged particles, dNchg/dηdϕ, and the average PTsum "associated" density, dPTsum/dηdϕ, in the "transMIN" region for "leading jet" events (defined in Fig. 5) as a function of the leading jet E_T. The "transMIN" correlations are very interesting. The fact that the "transMIN" densities rise with PTmaxT is somewhat surprising. However, both PYTHIA Tune A and HERWIG predict the rise. We expect "transMIN" region to be more sensitive to the "beam-beam remnant" and multiple parton interaction component of the "underlying event" and PYTHIA Tune A (with multiple parton interactions) again does a better job describing the data than HERWIG (without multiple parton interactions).

V. “Transverse” <P_T> versus Nchg

(1) Definition

We examine 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 $p_T > 0.5$ GeV/c and $|\eta| < 1$. Here we form the average transverse momentum, <p_T>, on an event-by-event basis and then plot the average <p_T> as a function of the charged multiplicity. The idea here is to look for correlations between multiplicity and <p_T>. If, for example, you have a mixture of “hard” and “soft” events then you expect that <p_T> will increase with multiplicity because demanding a large multiplicity will preferentially select the “hard” process that also has a larger <p_T>. On the other hand, it may be possible to get a high multiplicity in a “soft” collision so the rate that <p_T> 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 Run 1 CDF analysis that looks at this for “min-bias” collisions [10], but it has never been studied in the “transverse” region of a “hard” scattering interaction.

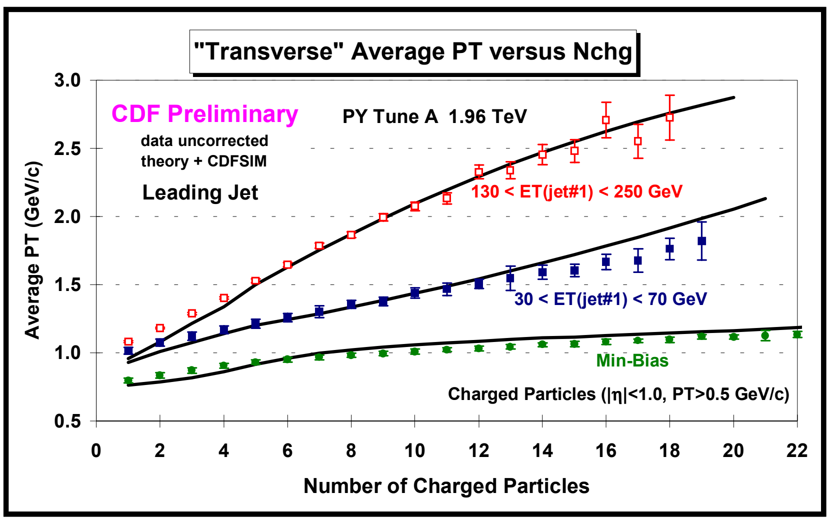


Fig. 29. Data on the average transverse momentum as a function number of particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the “transverse” region for “leading jet” events defined in Fig. 5 for $30 < E_T(\text{jet\#1}) < 70$ GeV and $130 < E_T(\text{jet\#1}) < 250$ GeV. Also 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 from Fig. 28. The theory curves correspond to PYTHIA Tune A at 1.96 TeV after CDFSIM.

(2) Overall “Transverse” Region

Fig. 29 shows Run 2 data on the <p_T> of charged particles versus the number of charged particles in “min-bias” collisions and the <p_T> of charged particles in the “transverse” region versus the number of charged particles in the “transverse” region for “leading jet” events with $30 < E_T(\text{jet\#1}) < 70$ GeV and $130 < E_T(\text{jet\#1}) < 250$ GeV compared with PYTHIA Tune A (after CDFSIM). The data are consistent with more “hard” scattering in the “transverse” region (*i.e.* initial and final-state radiation) than there is in an average “min-bias” collision.

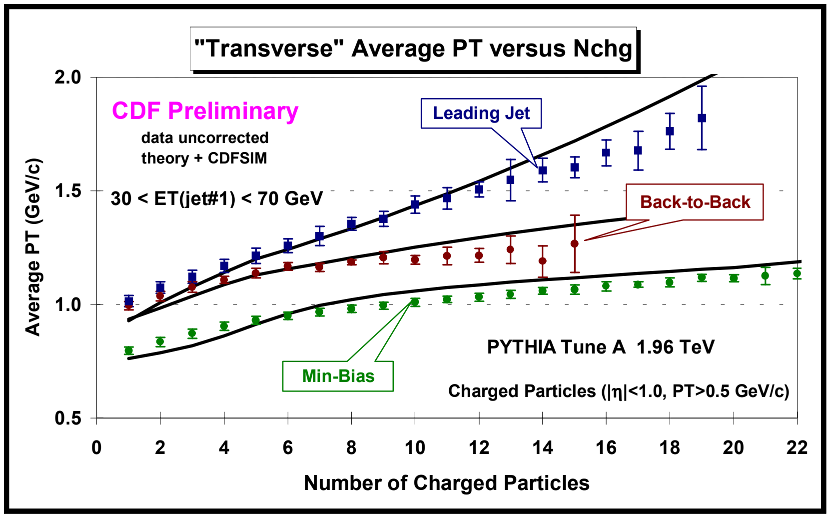


Fig. 30. Data on the average transverse momentum as a function of the number of particles for particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events and for "back-to-back" events defined in Fig. 5 for $30 < E_T(\text{jet\#1}) < 70$ 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 from Fig. 28. The theory curves correspond to PYTHIA Tune A at 1.96 TeV after CDFSIM.

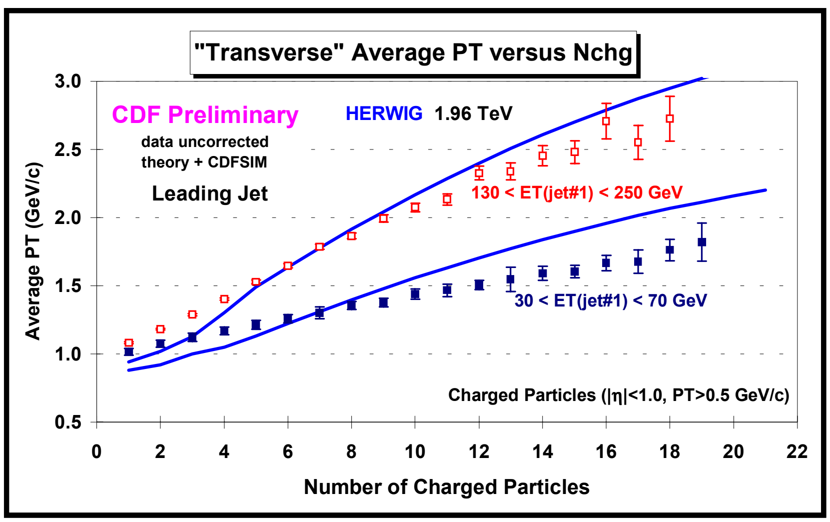


Fig. 31. Data on the average transverse momentum as a function of the number of particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events defined in Fig. 5 for $30 < E_T(\text{jet\#1}) < 70$ GeV and $130 < E_T(\text{jet\#1}) < 250$ GeV compared to HERWIG at 1.96 TeV (after CDFSIM).

Fig. 30 shows the $<p_T>$ of charged particles versus the number of charged particles in "min-bias" collisions and the $<p_T>$ 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 compared with PYTHIA Tune A (after CDFSIM). The "transverse" region of the "back-to-back" events looks more like an average "min-bias" collision, which is exactly what one expects since the "back-to-back" events suppress hard initial and final-state radiation.

Fig. 31 compares HERWIG (after CDFSIM) with the data on the $<p_T>$ of charged particles in the "transverse" region versus the number of charged particles in the "transverse" region for "leading jet" events with $30 < E_T(\text{jet\#1}) < 70$ GeV and $130 < E_T(\text{jet\#1}) < 250$ GeV.

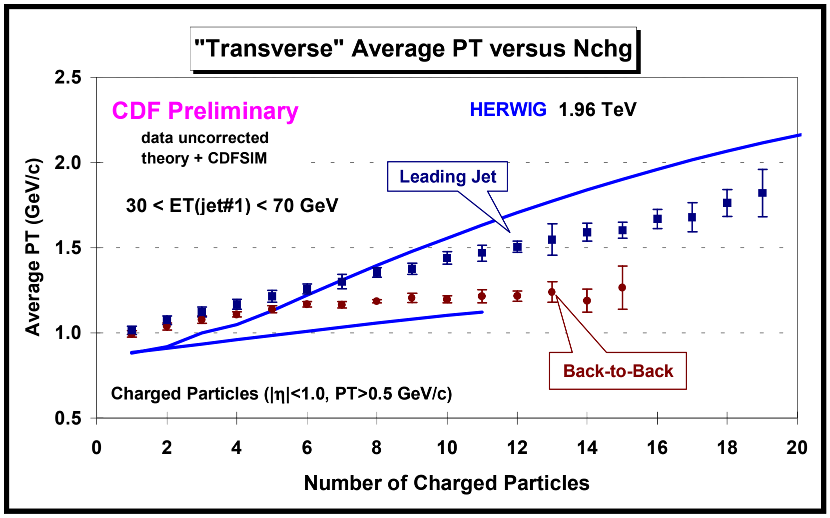


Fig. 32. Data on the average transverse momentum as a function of the number of particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" and "back-to-back" events defined in Fig. 5 for $30 < E_T(\text{jet}\#1) < 70$ GeV compared to HERWIG at 1.96 TeV (after CDFSIM).

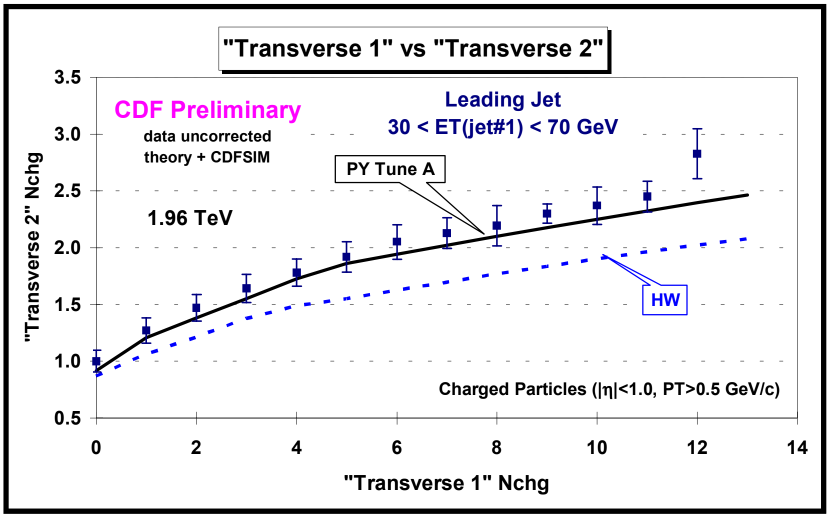
Fig. 32 compares HERWIG (after CDFSIM) with the data on the $\langle p_T \rangle$ of charged particles in the "transverse" region versus the number of charged particles in the "transverse" region for "leading jet" and "back-to-back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV.

(3) "Transverse 1" versus "Transverse 2"

Fig. 33 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. This is a new type of correlation. The fact that charged multiplicity in the "transverse 2" region increases with the charged multiplicity in the "transverse 1" region might simply be due to a high multiplicity in "transverse 1" biasing in favor of a harder over 2-to-2 scattering (i.e. higher P_T(hard)) which would result in a higher multiplicity in "transverse 2". However, we have seen that the average charged particle density does not change much as one increases ET(jet#1) (see Fig. 7).

Fig. 34 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. 35 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).



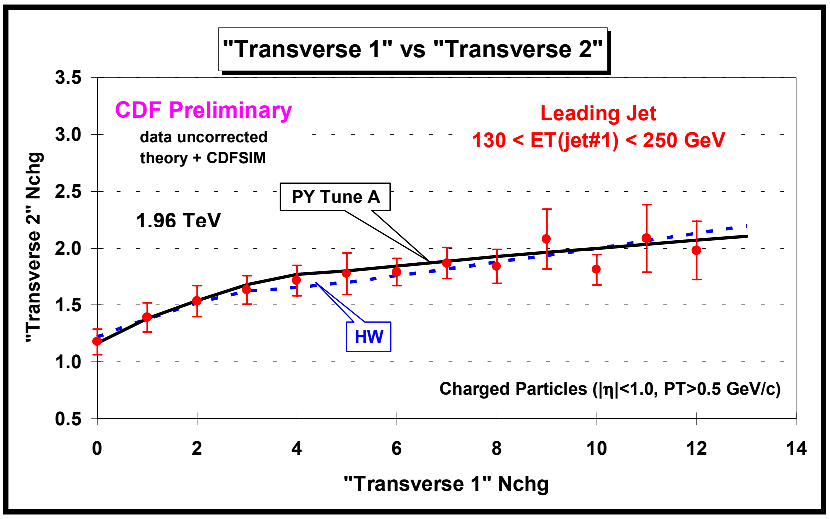


Fig. 33. Data on the average number of particles in the "transverse 2" region defined in Fig. 32 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events defined in Fig. 5 with $30 < E_T$(jet#1) < 70 GeV (*top*) and $130 < E_T$(jet#1) < 250 GeV (*bottom*). The theory curves correspond to PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM.

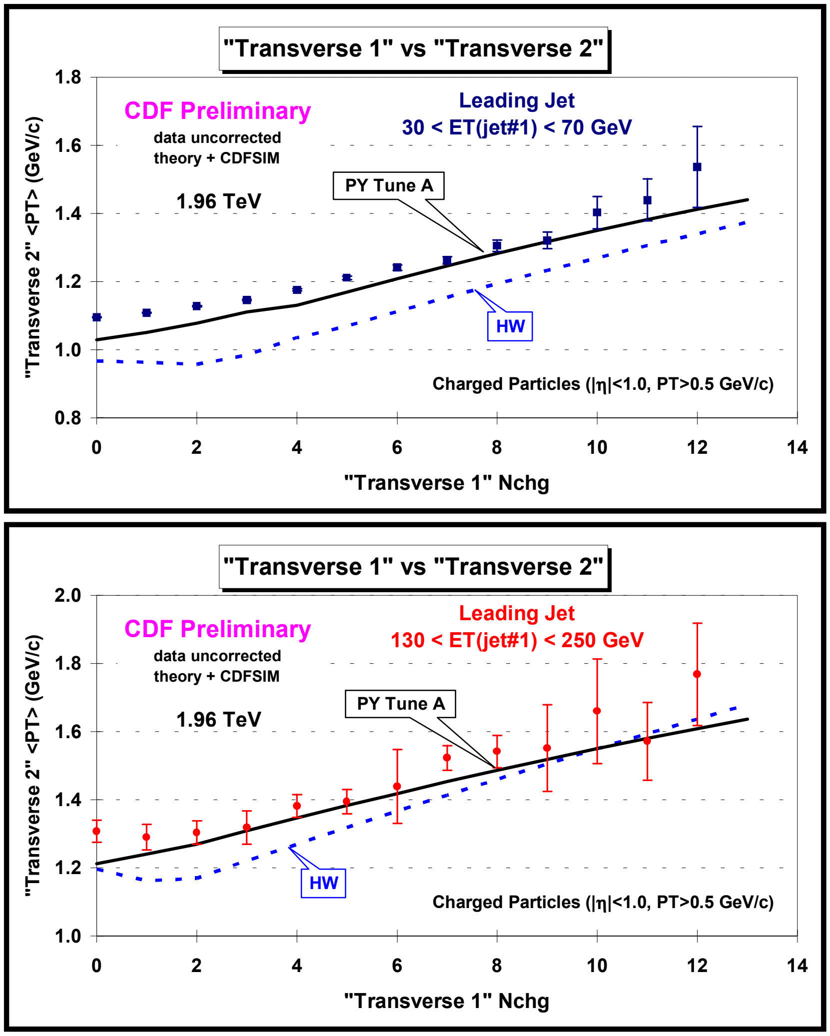


Fig. 34. Data on the average transverse momentum of particles in the "transverse 2" region defined in Fig. 32 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events defined in Fig. 5 with $30 < E_T(\text{jet\#1}) < 70$ 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.

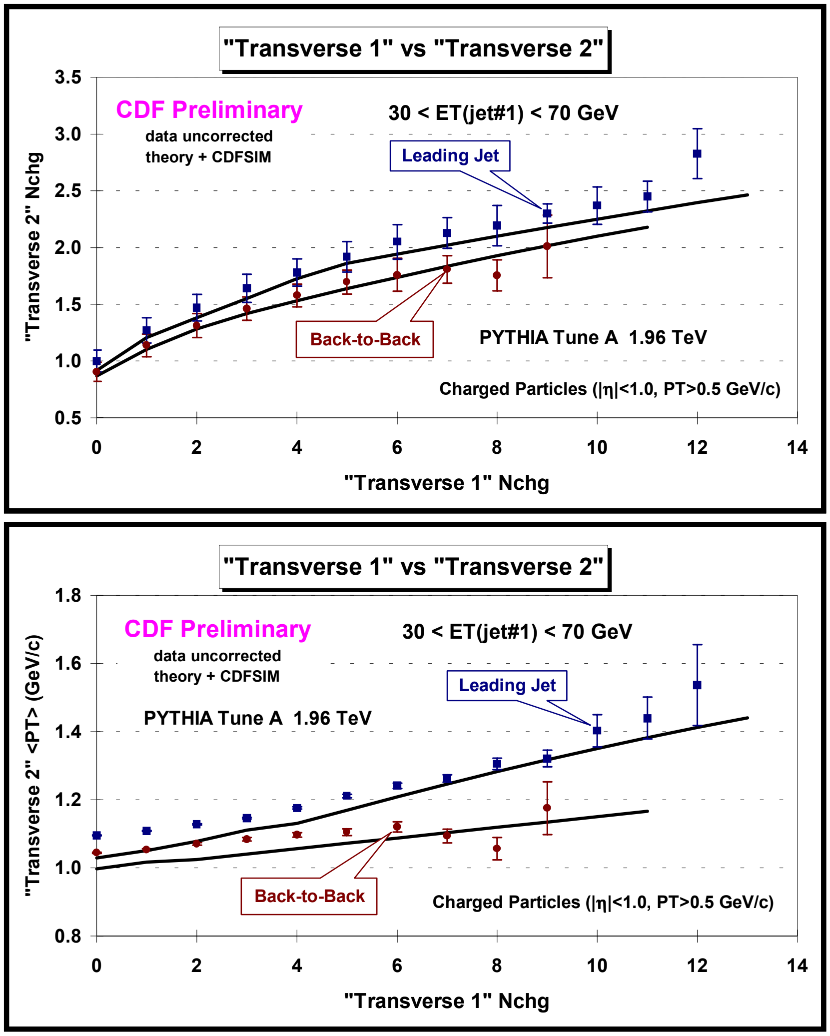
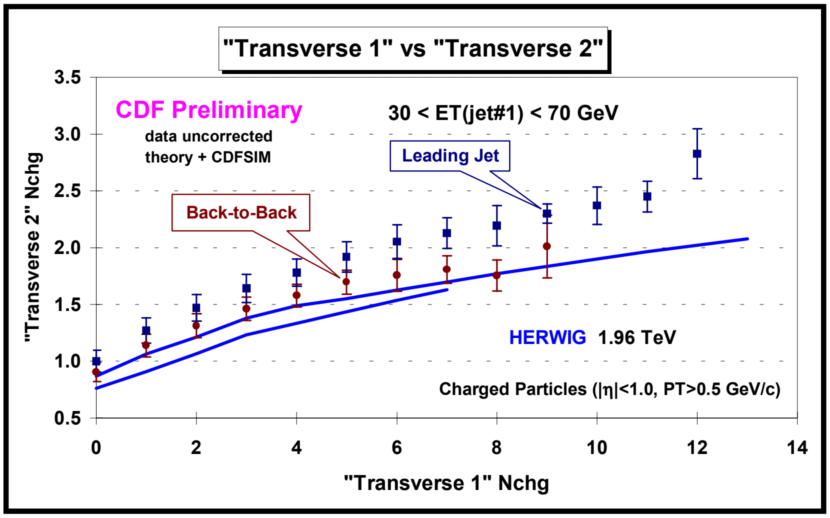


Fig. 35. Data on the average number of particles (*top*) and the average transverse momentum of particles (*bottom*) in the "transverse 2" region defined in Fig. 32 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events and "back-to-back" events defined in Fig. 5 with $30 < E_T(\text{jet\#1}) < 70$ GeV. The theory curves correspond to PYTHIA Tune A at 1.96 TeV (after CDFSIM).



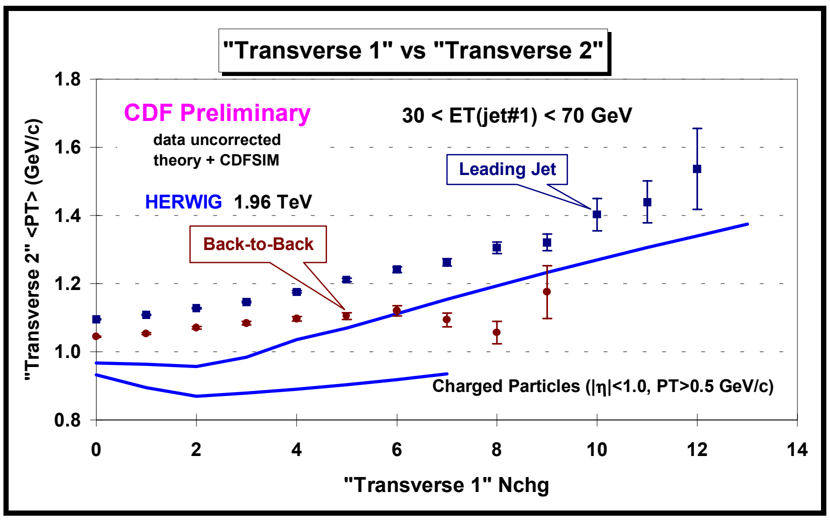


Fig. 36. Data on the average number of particles (*top*) and the average transverse momentum of particles (*bottom*) in the "transverse 2" region defined in Fig. 32 as a function of the number of particles in the "transverse 1" region for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events and "back-to-back" events defined in Fig. 5 with $30 < E_T(\text{jet\#1}) < 70$ GeV. The theory curves correspond to HERWIG at 1.96 TeV (after CDFSIM).

Fig. 36 shows the number and $<p_T>$ 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).

The "transverse 1" versus "transverse 2" correlations shown in Figs. 33-36 represent a new type of correlation. The fact that charged multiplicity and the $<p_T>$ in the "transverse 2" region increases with the charged multiplicity in the "transverse 1" region might simply be due to a high multiplicity in "transverse 1" biasing in favor of a harder over 2-to-2 scattering (*i.e.* higher P_T(hard)) which would result in a higher multiplicity and larger $<p_T>$ in "transverse 2". It is possible, however, that the correlations arises from the "beam-beam" remnants and 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 $<p_T>$ 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.

VI. Summary

In this note we talk a closer look at the “underlying event” in hard scattering proton-antiproton collisions at 1.96 TeV. This analysis is a continuation of our previous Run 2 analysis [5]. 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” 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 ($\Delta\phi_{12} > 150^o$) we are able to look closer at the “beam-beam remnant” 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” for E_T(jet#1) less than about 150 GeV, which was also observed in our published Run 1 analysis [2].

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, PTmaxT. The data show strong correlations. For E_T(jet#1) greater than about 50 GeV there is a higher density of charged particles “associated” with PTmaxT (*not including PTmaxT*) in the “transMAX” region than there is in the average “transverse” region. This means that there is a higher probability of finding a particle accompanying PTmaxT in the “transMAX” region than of finding a particle in the “transverse” region! These correlations are a strong indication of “jet” structure in the “underlying event” (*i.e.* “transverse” region) at PTmaxT values as low at 1.0 GeV/c. Of course, the “hard scattering” component of the “underlying event” (i.e. initial and final-state radiation) will produce “jets” structure. However, multiple parton interactions would also produce “jets” in the “underlying event”, some with very low ET. It is possible that even the “beam-beam remnants” are correlated and exhibit a “jet” structure. We are writing a companion CDF note [11] that looks at the “jet” structure in the “underlying event” in more detail. In that note we will compare the “jet” structure in “min-bias” collisions with the “jet” structure in the “underlying event” for both “leading jet” and “back-to-back” event.

The data presented here also show interesting correlations between the two “transverse” regions defined in Fig. 4. The “transMIN” densities rise with PTmaxT which is in the “transMAX” region (*i.e.* the other “transverse” region). Similarly, 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 might simply be due to high multiplicity in “transverse 1” or high PTmaxT in “transMAX” biasing in favor of a harder over 2-to-2 scattering (*i.e.* higher P_T(hard)) which would result in a higher multiplicity, larger PT_{sum}, and larger $\langle p_T \rangle$ other “transverse” region. However, we have seen that the average charged particle and PT_{sum} densities do not change much as one increases E_T(jet#1) (see Fig. 7). It is possible that the “transverse 1” versus "transverse 2" correlations arises from multiple parton interactions. A large multiplicity in the "transverse 1" region or high PTmaxT in "transMAX" would indicate that a hard collision with small impact parameter has occurred enhancing the probability of multiple parton interactions which would then cause an increased activity in the other "transverse" 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.

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