



THE UNDERLYING EVENT IN LARGE TRANSVERSE
MOMENTUM CHARGED JET AND
Z-BOSON PRODUCTION

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We study the behavior of the underlying event in large transverse momentum charged jet and Z-boson production at 1.8 TeV and compare with the QCD Monte-Carlo models. The data indicate that neither ISAJET or HERWIG produce enough charged particles (with $p_T > 0.5 \text{ GeV}/c$) from the “beam-beam remnant” component and that ISAJET produces too many charged particles from initial-state radiation. PYTHIA which uses multiple parton scattering to enhance the underlying event does the best job describing the data.

A typical hard scattering proton-antiproton collider event consists of outgoing hadrons that originate from the large transverse momentum partons (*i.e.*, outgoing hard scattering jets) and also hadrons that originate from the break-up of the proton and antiproton (*i.e.*, the beam-beam remnants). The “underlying event” is an interesting object that is not very well understood. In addition to the beam-beam remnants, it may contain hadrons resulting from initial-state radiation and from multiple parton scattering. PYTHIA¹, for example, uses multiple parton interactions as a way to enhance the activity of the underlying event. In this analysis we compare the overall event structure of charged particle jet and Z-boson events in proton-antiproton collisions at 1.8 TeV and study the underlying event. A large transverse momentum Z-boson event consists of large transverse momentum outgoing hadrons that originate from the away-side parton (*i.e.*, outgoing away-side jet) and the underlying event. As for the charged jet case, the underlying event consists of particles that arise from the beam-beam remnants, initial-state radiation, and multiple parton interactions. One would expect the underlying event to be roughly the same for large transverse momentum charged jet and Z-boson production.

In this analysis we consider only charged particles measured in the CDF central tracking chamber (CTC)². Our philosophy in comparing the Monte-Carlo models with the data is to select a region where the data is very clean. The CTC efficiency can vary substantially for very low p_T tracks and in dense high transverse momentum jets. To avoid this we have considered only the region $p_T > 0.5 \text{ GeV}/c$ and $|\eta| < 1$ where the CTC efficiency is high (estimated to be 92% efficient) and essentially independent of p_T and pseudorapidity, η , and we restrict ourselves to charged particle jets less with transverse momentum less than 50 GeV/c. The data presented here are uncorrected. Instead the theoretical Monte-Carlo predictions are

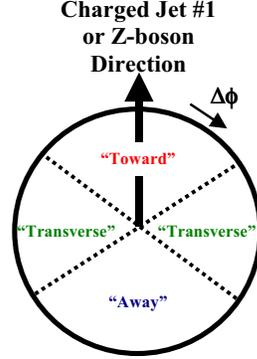


Fig. 1. Illustration of correlations in azimuthal angle $\Delta\phi$ relative to the direction of the leading charged particle jet in the event, chgjet1, or the Z-boson. The angle $\Delta\phi = \phi - \phi_{(\text{chgjet1 or Z})}$ is the relative azimuthal angle between charged particles and the direction of chgjet1 (or the Z-boson). The region $|\Delta\phi| < 60^\circ$ is referred to as “toward” chgjet1 (includes particles in chgjet1 and excludes the decay products of the Z-boson) and the region $|\Delta\phi| > 120^\circ$ is called “away” from chgjet1 (or the Z-boson). The “transverse” region is defined by $60^\circ < |\Delta\phi| < 120^\circ$. Each region, toward, transverse, and away covers the same range $|\Delta\eta| \times |\Delta\phi| = 2 \times 120^\circ$.

corrected for the CTC track finding efficiency and have an uncertainty (statistical plus systematic) of about 5%. The errors on the (uncorrected) data include both statistical and correlated systematic uncertainties. We examine only the charged particle component of jets and define charged particle jets as “circular regions” in η - ϕ space with radius $R = 0.7$. The transverse momentum of a charged particle jet is taken to be the *scalar* sum of the transverse momenta of the charged particles making up the jet.

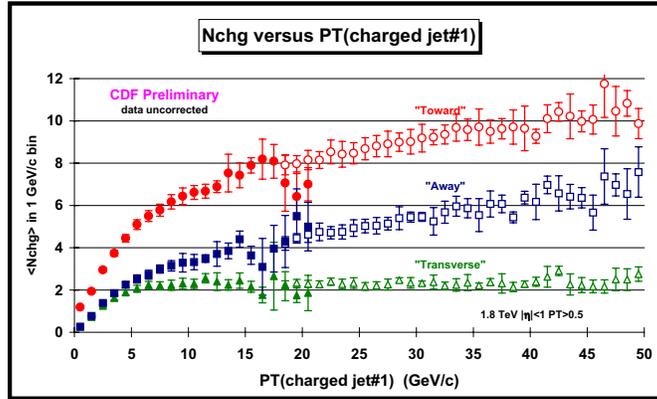


Fig. 2. The average number of toward ($|\Delta\phi| < 60^\circ$), transverse ($60^\circ < |\Delta\phi| < 120^\circ$), and away ($|\Delta\phi| > 120^\circ$) charged particles ($p_T > 0.5 \text{ GeV}/c$, $|\eta| < 1$, including chgjet1) as a function of the transverse momentum of the leading charged jet. Each point corresponds to the $\langle N_{\text{chg}} \rangle$ in a $1 \text{ GeV}/c$ bin. The solid (open) points are the Min-Bias (JET20) data. The toward, transverse, and away regions are defined in Fig. 1.

We study charged particle correlations in the azimuthal angle ϕ . We use the

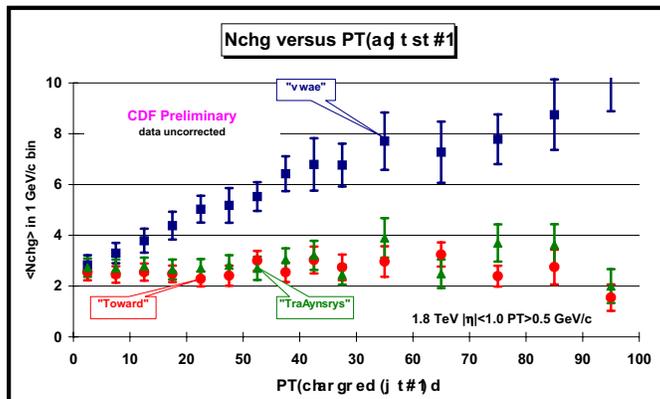


Fig. 3. The average number of toward ($|\Delta\phi| < 60^\circ$), transverse ($60^\circ < |\Delta\phi| < 120^\circ$), and away ($|\Delta\phi| > 120^\circ$) charged particles ($p_T > 0.5 \text{ GeV}/c$, $|\eta| < 1$, excluding the decay products of the Z-boson) as a function of the transverse momentum of the Z-boson. Each point corresponds to the $\langle N_{\text{chg}} \rangle$ in a $5 \text{ GeV}/c$ bin. The toward, transverse, and away regions are defined in Fig. 1.

direction of the leading charged particle jet (or the Z-boson) in each event to define a “transverse” region of η - ϕ space that is very sensitive to the underlying event. This transverse region is approximately normal the plane of the hard 2-to-2 parton scattering. As illustrated in Fig. 1, the angle $\Delta\phi = \phi - \phi_{(\text{chgjet1 or Z})}$ is defined to be the relative azimuthal angle between charged particles and the direction of the leading charged particle jet (or Z-boson). We label the region $|\Delta\phi| < 60^\circ$ as “toward” chgjet1 (or Z-boson) and the region $|\Delta\phi| > 120^\circ$ as “away” from chgjet1 (or Z-boson). The “transverse” region is defined by $60^\circ < |\Delta\phi| < 120^\circ$. Each region, toward, transverse, and away covers the same range $|\Delta\eta| \times |\Delta\phi| = 2 \times 120^\circ$. For the charged jet case the toward region includes the particles from chgjet1 as well as particles from the underlying event. For the Z-boson case we exclude the decay products of the Z-boson so the toward region is a direct measure of the underlying event. As we will see, the transverse region for both the charged jet and Z-boson case is also very sensitive to the underlying event. The away region is a mixture of the underlying event and the away-side hard scattering jet.

Fig. 2 shows the charged jet data on the average number of charged particles ($p_T > 0.5 \text{ GeV}/c$ and $|\eta| < 1$), respectively, as a function of $P_T(\text{chgjet1})$ for the three regions for the three regions defined in Fig. 1. As expected the toward region contains the most particles since it includes the leading charged particle jet. The charged particle density in the transverse region rises very rapidly at low $P_T(\text{chgjet1})$ values and then forms an approximately constant “plateau” for $P_T(\text{chgjet1}) > 6 \text{ GeV}/c$. Of course, the charged particle density in all regions is forced to go to zero as $P_T(\text{chgjet1})$ goes to zero. If the leading charged particle jet has no particles then there are no charged particles anywhere. Fig. 3 shows the Z-boson data on the average number of charged particles ($p_T > 0.5 \text{ GeV}/c$ and $|\eta| < 1$), respectively, as a function of $p_T(Z)$ for the three regions defined in Fig. 1. The Z-boson event structure is, of course, quite different from the charged jet case.

For Z-boson production the toward and transverse regions are almost the same and the activity in these regions does not vanish as the transverse momentum of the Z-boson becomes small.

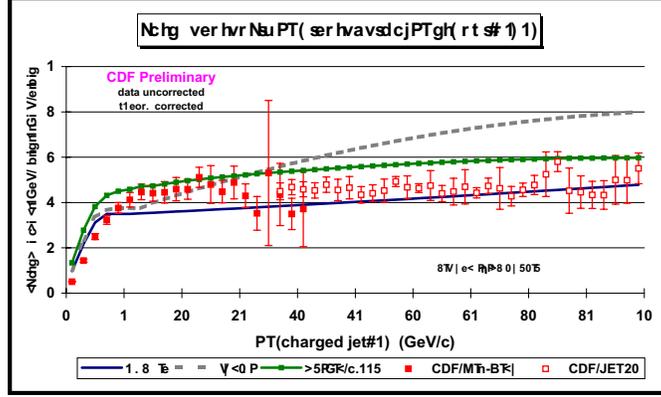


Fig. 4. Data from Fig. 2 on the average number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) as a function of $P_T(\text{chgjet1})$ (leading charged jet) for the transverse region defined in Fig. 1 compared with the QCD hard scattering Monte-Carlo predictions of HERWIG, ISAJET, and PYTHIA 6.115.

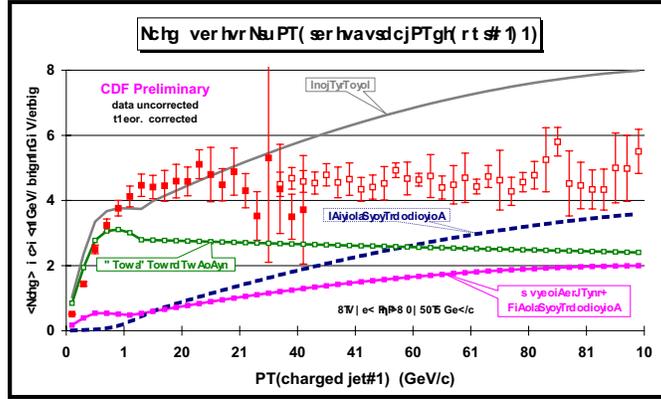


Fig. 5. Data from Fig. 2 on the average number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) as a function of $P_T(\text{chgjet1})$ (leading charged jet) for the transverse region defined in Fig. 1 compared with the QCD hard scattering Monte-Carlo predictions of ISAJET. The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam particles (beam-beam remnants), charged particles that arise from initial-state radiation, and charged particles that result from the outgoing jets plus final-state radiation.

Fig. 4 compares the charged jet transverse $\langle N_{\text{chg}} \rangle$ with the QCD hard scattering Monte-Carlo predictions of HERWIG 5.9³, ISAJET 7.32⁴, and PYTHIA 6.115, where we have chosen $p_T(\text{hard}) > 3$ GeV/c for the hard scattering Monte-Carlo models. Instead of a plateau, ISAJET predicts a rising transverse $\langle N_{\text{chg}} \rangle$ and gives too much activity at large $P_T(\text{chgjet1})$ values. We expect the transverse region to be composed predominately from particles that arise from the beam-beam remnants

and from initial-state radiation. This is clearly the case as can be seen in Fig. 5 where the predictions of ISAJET for the transverse region are divided into three categories: beam-beam remnants, initial-state radiation, and outgoing jets plus final-state radiation. It is interesting to see that it is the beam-beam remnants that are producing the approximately constant plateau. The contributions from initial-state radiation and from the outgoing hard scattering jets both increase as $P_T(\text{chgjet1})$ increases. In fact, for ISAJET it is the sharp rise in the initial-state radiation component that is causing the disagreement with the data for $P_T(\text{chgjet1}) > 20 \text{ GeV}/c$.

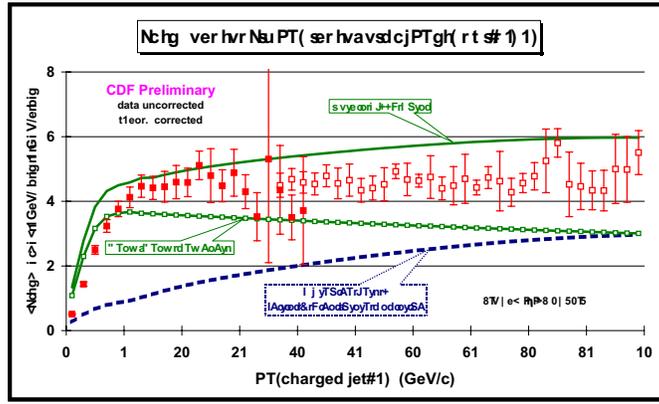


Fig. 6. Data from Fig. 2 on the average number of charged particles ($p_T > 0.5 \text{ GeV}/c$, $|\eta| < 1$) as a function of $P_T(\text{chgjet1})$ (leading charged jet) for the transverse region defined in Fig. 1 compared with the QCD hard scattering Monte-Carlo predictions of PYTHIA 6.115. The predictions of PYTHIA are divided into two categories: charged particles that arise from the break-up of the beam particles (beam-beam remnants), and charged particles that result from the outgoing jets plus initial and final-state radiation (hard scattering component). For PYTHIA the beam-beam remnants include contributions from multiple parton scattering.

For PYTHIA it makes no sense to distinguish between particles that arise from initial-state radiation from those that arise from final-state radiation, but one can separate the “hard scattering component” from the beam-beam remnants. For PYTHIA the beam-beam remnants include contributions from multiple parton scattering. Fig. 6 compares the charged jet transverse $\langle N_{\text{chg}} \rangle$ with the QCD hard scattering predictions from PYTHIA 6.115. Here the predictions are divided into two categories: charged particles that arise from the break-up of the beams (beam-beam remnants), and charged particles that result from the outgoing jets plus initial and final-state radiation (hard scattering component). As was the case with ISAJET the beam-beam remnants form the approximately constant plateau and the hard scattering component increase as $P_T(\text{chgjet1})$ increases. However, the hard scattering components of PYTHIA (and HERWIG) do not rise nearly as fast as the hard scattering component of ISAJET. There are two reasons why the hard scattering component of ISAJET is different from PYTHIA and HERWIG. The first is due to different fragmentation schemes. ISAJET uses independent fragmentation, which produces too many soft hadrons when partons begin to overlap. The second

difference arises from the way the QCD Monte-Carlo produce “parton showers”. ISAJET uses a leading-log picture in which the partons within the shower are ordered according to their invariant mass. Kinematics requires that the invariant mass of daughter partons be less than the invariant mass of the parent. HERWIG and PYTHIA modify the leading-log picture to include “color coherence effects” which leads to “angle ordering” within the parton shower. Angle ordering produces less high p_T radiation within a parton shower which is what is seen in Fig. 4.

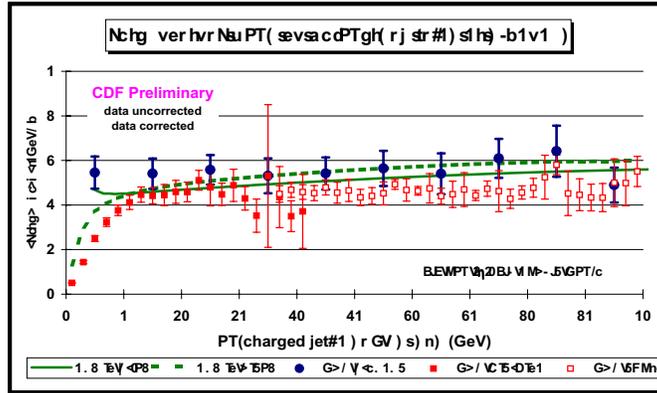


Fig. 7. Comparison of the charged jet data from Fig. 2 and the Z-boson data from Fig. 3 on the average number of charged particles ($p_T > 0.5 \text{ GeV}/c$, $|\eta| < 1$) for the transverse region defined in Fig. 1. The plot shows the QCD hard scattering Monte-Carlo predictions of PYTHIA 6.115 for charged jet (dashed) and “Z-jet” production (solid).

Fig. 7 shows a comparison of the charged jet data from Fig. 2 and the Z-boson data from Fig. 3 on the average number of charged particles for the transverse region together with the charged jet and “Z-jet” predictions from PYTHIA 6.115. For $P_T(\text{chgjet1})$ and $p_T(Z)$ greater than $5 \text{ GeV}/c$ the charged jet and Z-boson data roughly agree. For the Z-boson case the beam-beam remnant component is essentially flat down to $p_T(Z)$ equal to zero. For the charged jet case, all components are forced to go to zero as $P_T(\text{chgjet1})$ goes to zero. For $P_T(\text{chgjet1})$ or $p_T(Z)$ around $20 \text{ GeV}/c$ there are about 4 charged particles per unit rapidity with $p_T > 0.5 \text{ GeV}/c$ in the underlying event.

Both the charged jet and Z-boson data suggest that ISAJET produces too many charged particles from initial-state radiation. Because ISAJET uses independent fragmentation and HERWIG and PYTHIA do not and HERWIG and PYTHIA use angle ordering in parton showers and ISAJET does not; there are clear differences in the hard scattering component (mostly initial-state radiation) of the underlying event between ISAJET and the other two Monte-Carlo models. Here the data strongly favor HERWIG and PYTHIA over ISAJET.

The data indicate that neither ISAJET or HERWIG produce enough charged particles from the beam-beam remnant component. Since we are considering only charged particles with $p_T > 0.5 \text{ GeV}/c$, the number of particles is related to the transverse momentum distribution of the beam-beam remnant contribution. A

steeper p_T distribution means less particles with $p_T > 0.5 \text{ GeV}/c$. The beam-beam remnant component of both ISAJET and HERWIG has too steep of a p_T distribution. PYTHIA which uses multiple parton scattering to enhance the beam-beam remnant component does the best job describing the data. It is, of course, understandable that the Monte-Carlo models might be somewhat off on the parameterization of the beam-beam remnants. This component cannot be calculated from perturbation theory and must be determined from data.

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