

# Studying the Underlying Event at the Tevatron

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## Abstract

CDF Run II data for the underlying event associated with Drell-Yan lepton pair production are studied as a function of the lepton-pair transverse momentum. The data are compared with a previous analysis on the behavior of the underlying event in high transverse momentum jet production and also with several other QCD Monte-Carlo models. The goal is to provide data that can be used to tune and improve the QCD Monte-Carlo models of the underlying event, which is especially important now for the startup of the Large Hadron Collider.

## 5 Introduction: the Underlying Event

In order to find ‘new’ physics at a hadron-hadron collider it is essential to have Monte-Carlo models that simulate accurately the ‘ordinary’ QCD hard-scattering events. To do this one must not only have a good model of the hard scattering part of the process, but also of the underlying event.

A typical 2-to-2 hard scattering event is a proton-antiproton collision at the hadron colliders as shown in the Fig. 1, all happening inside the radius of a proton. In addition to the two hard scattered outgoing partons, which fragment into jets - there is initial and final state radiation (caused by bremsstrahlung and gluon emission), multiple parton interaction (additional 2-to-2 scattering within the same event), ‘beam beam remnants’ (particles that come from the breakup of the proton and antiproton, from the partons not participating in the primary hard scatter). We define the ‘underlying event’ [1] as everything except the hard scattered components, which includes the ‘beam-beam remnants’ (or the BBR) plus the multiple parton interaction (or the MPI). However, it is not possible on an event-by-event basis to be certain which particles came from the underlying event and, which particles originated from the hard scattering. The ‘underlying event’ (*i.e.* BBR plus MPI) is an unavoidable background to most collider observables. For example, at the Tevatron both the inclusive jet cross section and the b-jet cross section, as well as isolation cuts and the measurement of missing energy depend sensitively on the underlying event. A good understanding of it will lead to more precise measurements at the Tevatron and the LHC.

Experimentally it is possible to take advantage of the topological structure of hadron-hadron collisions to study the underlying event. The direction of the Z boson is used to isolate regions of  $\eta - \phi$  space that are sensitive to the underlying event. The angle  $\Delta\phi = \phi - \phi_Z$  is the relative azimuthal angle between charged particles coming from the underlying event and the direction of Z boson, as in Fig. 2 (left). We split the central region defined between  $|\eta| < 1$  as follows,

- $|\Delta\phi| < 60^\circ$  as the toward region.

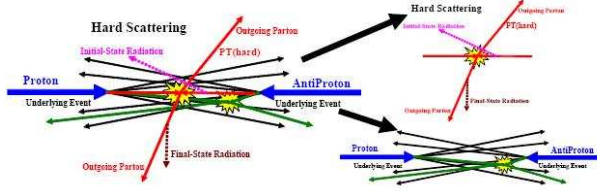


Figure 10: A typical 2-2 hard scattering process

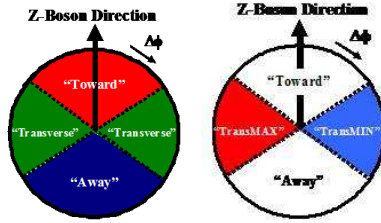


Figure 11: On the left, dividing the central region, with relative to the Z boson direction and on the right, TransMAX and transMIN regions.

- $60^\circ < |\Delta\phi| < 120^\circ$  as the transverse region. And,
- $|\Delta\phi| > 120^\circ$  as the away region.

As illustrated in Fig. 2 (right), we define MAX and MIN transverse regions which help to separate the hard component (initial and final-state radiation) from the beam-beam remnant 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 of charged particles, on an event by event basis. One expects that the transMAX region will pick up the hardest initial or final-state radiation while both the transMAX and transMIN regions should receive beam-beam remnant contributions. Hence one expects the transMIN region to be more sensitive to the beam-beam remnant component of the underlying event, while the transMAX minus the transMIN (*i.e.*, transDIF) is very sensitive to hard initial and final-state radiation. This idea, was first suggested by Bryan Webber and Pino Marchesini [2], and implemented in a paper by Jon Pumplin [3].

For hard scattered jets the transverse regions are most sensitive to underlying events, since they are perpendicular to the plane of 2-to-2 hard scattering. For Drell-Yan its easy to identify and remove leptons (since they are the colorless components) from the transverse and toward (which can not be done for dijet events, as the leading jet is itself in toward region) regions and use them to study the underlying event. So we can see that Drell-Yan events are a clean probe of the underlying events.

## 6 Comparing data with QCD Monte Carlo Models

### 6.1 The underlying event as a function of lepton pair $p_T$

We looked at the charged particles in the range  $p_T > 0.5 \text{ GeV}/c$  and  $|\eta| < 1$ , at the region of Z-boson, defined as  $70 \text{ GeV}/c^2 < M_{ll} < 110 \text{ GeV}/c^2$ , in the ‘toward’, ‘away’ and ‘transverse’ regions, as defined in Fig. 2. The electron and muon selections are based on the standard CDF high  $p_T$  electron and muon selection criteria. The lepton pairs are formed by oppositely charged leptons, with the requirement that both the leptons came from the same primary collision. We use a time of flight [4] cosmic filter to eliminate cosmic muons, as the time difference between the muons recorded in the upper and lower half of the detector is expected to be very small for muons not coming from cosmic rays. The  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$  data sample contains backgrounds mainly from QCD jets and W+jets. Studies [5] have shown that these backgrounds are negligible at the region of Z boson. We use the ratio of the generator level Monte Carlo result [6] and the detector level Monte Carlo result as our correction factor for correcting the data back to the particle level. We analyzed data corresponding to the luminosity of approximately  $2.7 \text{ fb}^{-1}$ .

The underlying event observables are found to be reasonably flat with the increasing lepton pair transverse momentum in the transverse and toward regions, but goes up in the away region to balance the lepton pairs.

In Fig. 3, we looked at the two observables corresponding to the underlying event, the number of charged particle density and the charged transverse momentum sum density in the transverse region, compared with PYTHIA [7] tunes A and AW [8], HERWIG [9] without MPI and a previous CDF analysis on leading jet underlying event results. We overlay the results for all the regions in Fig. 4. In Fig. 5 and 6, we look at the same observables in transMAX, transMIN, and transDIF regions. Overall, we can see that PYTHIA tune AW does a good job of reproducing the data. HERWIG (without MPI) does not produce enough activity in the transverse region for either process. There is no final-state radiation in Z-boson production so that the lack of MPI becomes more evident. HERWIG (with JIMMY [10] MPI) agrees with tune AW for the scalar pT sum density in the toward and transMIN regions. However, it produces too much charged particle density in these regions. HERWIG (with JIMMY MPI) fits the  $p_T$  sum density, but it does so by producing too many charged particles (*i.e.* it has too soft of a  $p_T$  spectrum in these regions). This can be seen in Fig. 7 which shows the data for Z-boson events on the average charged particle  $p_T$  and the average maximum charged particle  $p_T$ , for the transverse region compared with the QCD Monte Carlo models. So the  $p_T$  distributions in the transverse region are too soft, resulting in an average  $p_T$  and average  $p_T$  maximum that are too small. Comparing HERWIG (without MPI) with HERWIG (with JIMMY MPI) clearly shows the importance of MPI in these regions.

We also compared them with leading jet underlying event results [11] and observed reasonably close agreement - which may indicate the universality of underlying event modeling. However, at low  $p_T$ , we see a difference. If the leading jet has no transverse momentum then there are no charged particles, we just get min-bias events. There are a lot of low transverse momentum jets and for  $p_T(\text{jet}\#1) < 30 \text{ GeV}/c$  the leading jet is not always the jet resulting

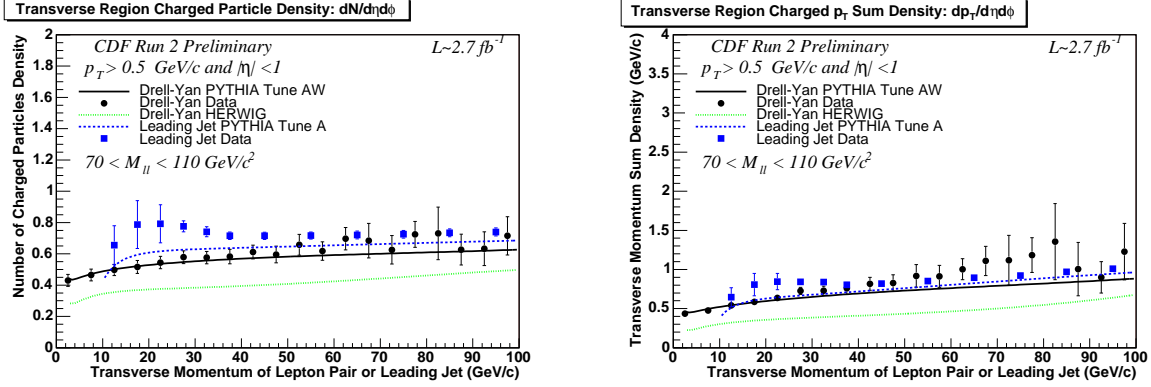


Figure 12: Drell-Yan underlying event plots, charged particle multiplicity at the top and the charged  $p_T$  sum at the bottom.

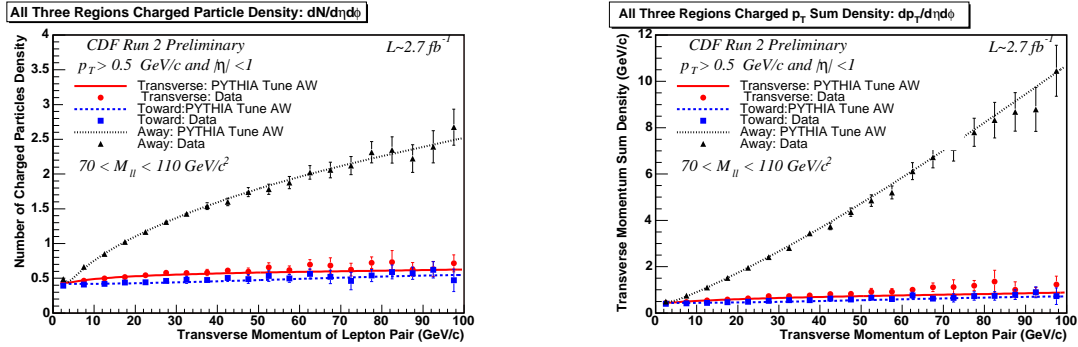


Figure 13: Overlaying all three regions, charged particle multiplicity at the top and the charged  $p_T$  sum at the bottom.

from the hard 2-to-2 scattering. This produces a bump in the transverse density at low  $p_T$ .

## 6.2 Correlation studies

The rate of change of  $\langle p_T \rangle$  versus charged multiplicity is a measure of the amount of hard versus soft processes contributing to collisions and it is sensitive to the modeling of the multiple parton interactions [12]. This variable is the most poorly reproduced variable by the available Monte-Carlo generators. If only the soft beam-beam remnants contributed to min-bias collisions then  $\langle p_T \rangle$  would not depend on charged multiplicity. If one has two processes contributing, one soft (beam-beam remnants) and one hard (hard 2-to-2 parton-parton scattering), then demanding large multiplicity would preferentially select the hard process and lead to a high  $\langle p_T \rangle$ . However, we see that with only these two processes  $\langle p_T \rangle$  increases much too rapidly as a function of multiplicity. Multiple-parton interactions provides another mechanism for producing large multiplicities that are harder than the beam-beam remnants, but not as hard as the primary 2-to-2 hard scattering.

Fig. 8(top) shows the data corrected to the particle level on the average  $p_T$  of charged particles versus the multiplicity for charged particles with  $p_T > 0.5 \text{ GeV}/c$  and  $|\eta| < 1$  for Z-boson events from this analysis. HERWIG (without MPI) predicts the  $\langle p_T \rangle$  to rise too

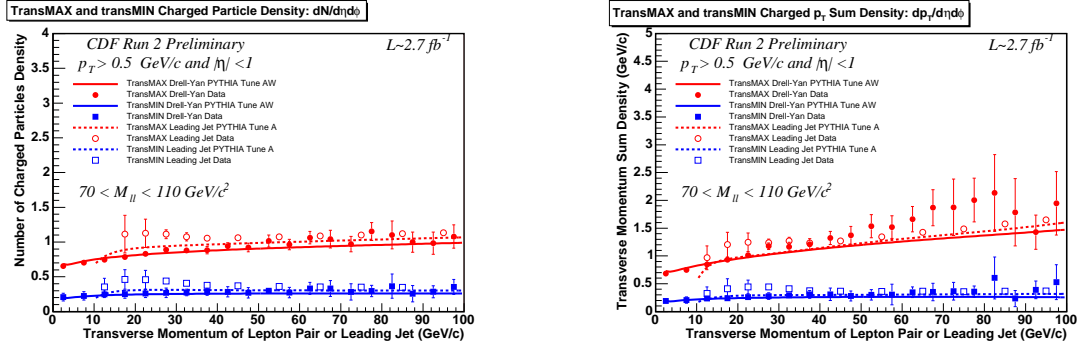


Figure 14: TransMAX and transMIN regions, charged particle multiplicity at the top and the charged  $p_T$  sum at the bottom.

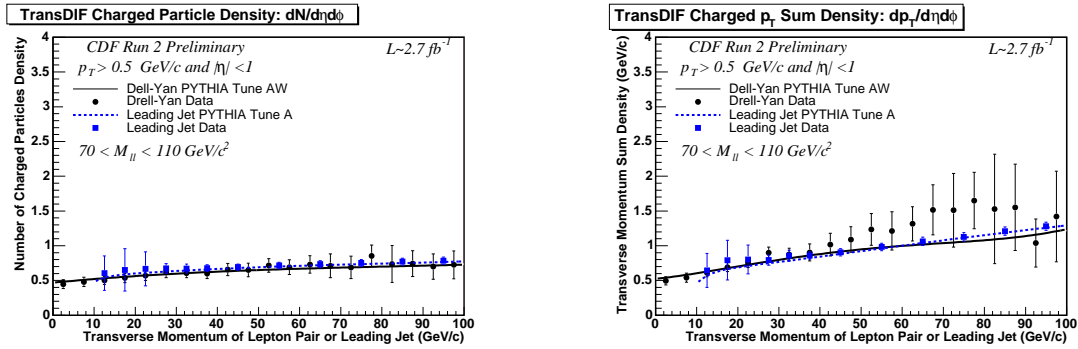


Figure 15: TransDIF regions, charged particle multiplicity at the top and the charged  $p_T$  sum at the bottom.

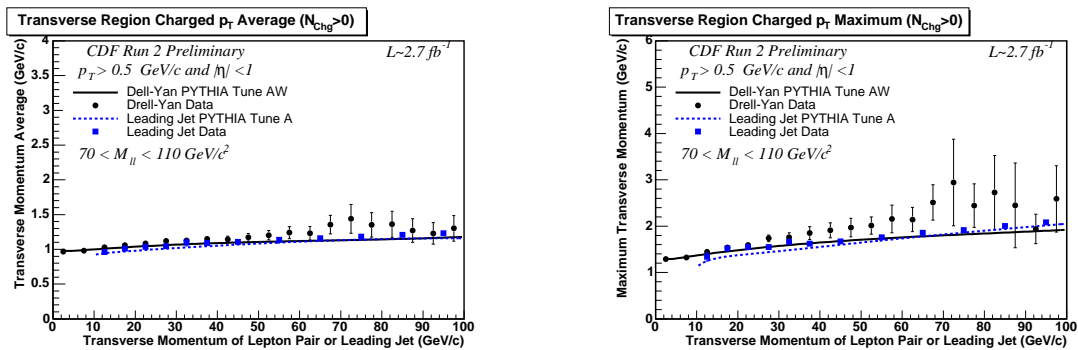


Figure 16: Drell-Yan underlying event plots, charged particle  $\langle p_T \rangle$  at the top and the charged  $p_T$  maximum at the bottom.

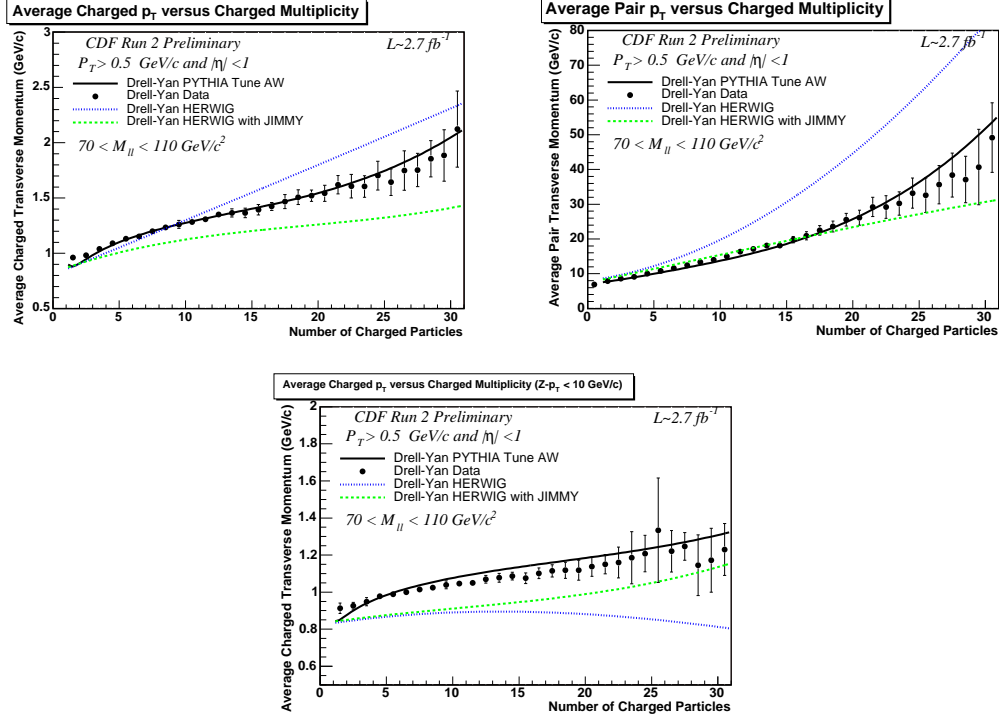


Figure 17: Charged multiplicity against charged transverse momentum average correlation plots.

rapidly as the multiplicity increases. For HERWIG (without MPI) large multiplicities come from events with a high  $p_T$  Z-boson and hence a large  $p_T$  ‘away-side’ jet. This can be seen clearly in Fig. 8(middle) which shows the average  $p_T$  of the Z-boson versus the charged multiplicity. Without MPI the only way of getting large multiplicity is with high  $p_T(Z)$  events. For the models with MPI one can get large multiplicity either from high  $p_T(Z)$  events or from MPI and hence  $\langle p_T(Z) \rangle$  does not rise as sharply with multiplicity in accord with the data. PYTHIA tune AW describes the Z-boson data fairly well. Fig. 8(bottom) shows the data corrected to the particle level on the average  $p_T$  of charged particles versus the multiplicity for charged particles with  $p_T > 0.5 \text{ GeV}/c$  and  $|\eta| < 1$  for Z-boson events in which  $p_T(Z) < 10 \text{ GeV}/c$ . Regardless of all the improvements in the comprehension of low- $p_T$  production, the models are still unable to reproduce second order quantities such as final state particle correlations. We see that  $\langle p_T \rangle$  still increases as the multiplicity increases although not as fast. If we require  $p_T(Z) < 10 \text{ GeV}/c$ , then HERWIG (without MPI) predicts that the  $\langle p_T \rangle$  decreases slightly as the multiplicity increases. This is because without MPI and without the high  $p_T$  ‘away-side’ jet which is suppressed by requiring low  $p_T(Z)$ , large multiplicities come from events with a lot of initial-state radiation and the particles coming from initial-state radiation are ‘soft’. PYTHIA tune AW describes the behavior of  $\langle p_T \rangle$  versus the multiplicity fairly well even when we select  $p_T(Z) < 10 \text{ GeV}/c$ . This strongly suggests that MPI are playing an important role in both these processes.

## 7 Summary and Conclusions

We are making good progress in understanding and modeling the softer physics. CDF tunes A and AW describe the data very well, although we still do not yet have a perfect fit to all the features of the CDF underlying event data. Future studies should focus on tuning the energy dependence for the event activity in the underlying event, which at the moment seems to be one of the least understood aspects of all the models. The underlying event is expected to be much more active in LHC and it is critical to have sensible underlying event models containing our best physical knowledge and intuition, tuned to all relevant available data.

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