CDF Run 2 Monte-Carlo Tunes

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Abstract: Several CDF Run 2 PYTHIA 6.2 tunes (with multiple parton interactions) are presented and compared with HERWIG (without multiple parton interactions) and with the ATLAS PYTHIA tune (with multiple parton interactions). Predictions are made for the "underlying event" in high p_T jet production and in Drell-Yan lepton-pair production at the Tevatron and the LHC.

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 beam-beam remnants and the multiple parton interactions. The "underlying event" is an unavoidable background to most collider observables and a good understanding of it will lead to more precise measurements at the Tevatron and the LHC. 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 [1,2]. The "hard scattering" component of the event consists of particles that result from the hadronization of the two outgoing partons (*i.e.* the initial two "jets") plus the particles that arise from initial and final state radiation (*i.e.* multijets). The "underlying event" consists of particles that arise from the "beam-beam remnants" and from multiple parton interactions (MPI). Of course, in a given event it is not possible to uniquely determine the origin of the outgoing particles and whatever observable one chooses to study inevitably receives contributions from both the hard component and the underlying event. In studying observables that are sensitive to the underlying event one learns not only about the "beam-beam remnants" and multiple parton interactions, but also about hadronization and initial and final state radiation.

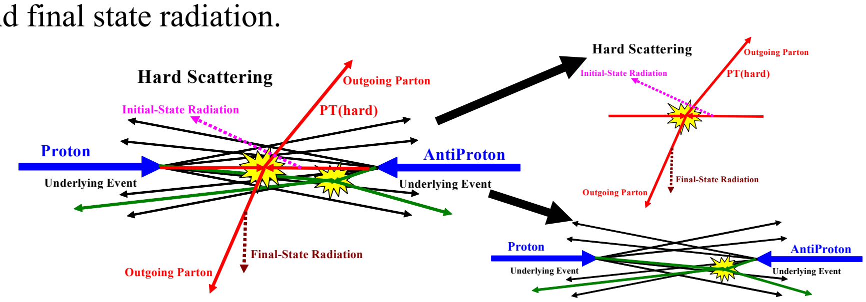

Fig. 1. Illustration of the way QCD Monte-Carlo models simulate a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, P_T(hard), has occurred. The "hard scattering" component of the event consists of particles that result from the hadronization of the two outgoing partons (*i.e.* the initial two "jets") plus the particles that arise from initial and final state radiation (*i.e.* multijets). The "underlying event" consists of particles that arise from the "beam-beam remnants" and from multiple parton interactions.

At CDF we are working to understand and model the underlying event at the Tevatron. We use the topological structure of hadron-hadron collisions to study the underlying event [3-5]. The direction of the leading calorimeter jet is used to

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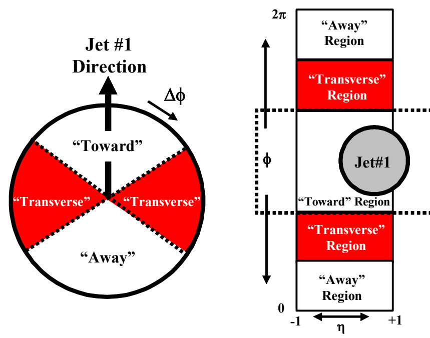

Fig. 2. Illustration of correlations in azimuthal angle $\Delta\phi$ relative to the direction of the leading jet (MidPoint, R = 0.7, f_{merge} = 0.75) in the event, jet#1. The angle $\Delta\phi = \phi - \phi$jet#1 is the relative azimuthal angle between charged particles and the direction of jet#1. The "transverse" region is defined by $60^o < |\Delta\phi| < 120^o$ and $|\eta| < 1$. The "transverse" region 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 $|\eta(\text{jet\#1})| < 2$.

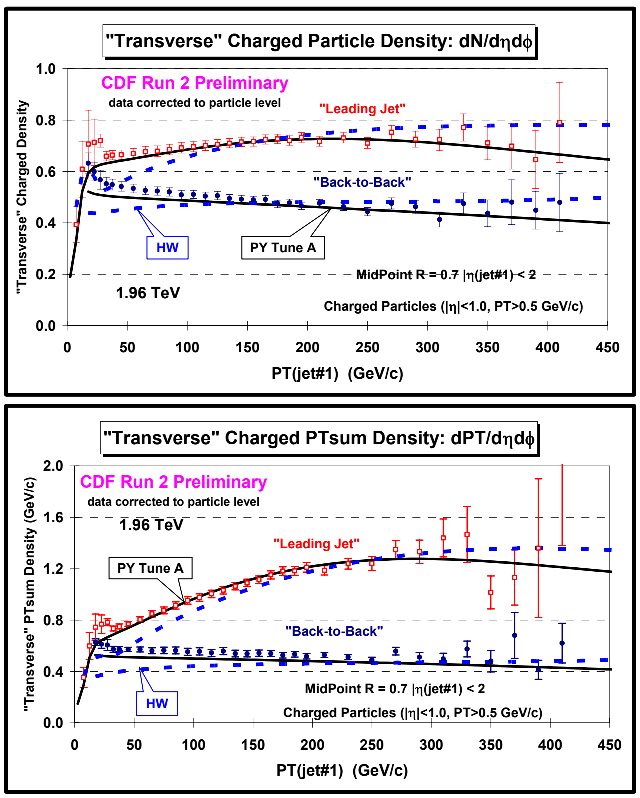

Fig. 3. CDF Run 2 data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$ (*top*), and the charged PTsum density, $dPT/d\eta d\phi$ (*bottom*), with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" and "back-to-back" events as a function of the leading jet P_T compared with PYTHIA Tune A and HERWIG. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and compared with the theory at the particle level (*i.e.* generator level).

isolate regions of η-ϕ space that are sensitive to the underlying event. As illustrated in Fig. 2, 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 "transverse" region is perpendicular to the plane of the hard 2-to-2 scattering and is therefore very sensitive to the underlying event. Furthermore, we consider two classes of events. We refer to events in which there are no restrictions placed on the second and third highest P_T jets (jet#2 and jet#3) as "leading jet" events. Events with at least two jets with $P_T > 15$ GeV/c where the leading two jets are nearly "back-to-back" ($|\Delta\phi_{12}| > 150^o$) with P_T(jet#2)/P_T(jet#1) > 0.8 and P_T(jet#3) < 15 GeV/c are referred to as "back-to-back" events. "Back-to-back" events are a subset of the "leading jet" events. The idea here is to suppress hard initial and final-state radiation thus increasing the sensitivity of the "transverse" region to the "beam-beam remnant" and the multiple parton scattering component of the underlying event.

Fig. 3 compares the data on the density of charged particles and the charged PTsum density in the "transverse" region for "leading jet" and "back-to-back" events with PYTHIA Tune A (with multiple parton interactions) and HERWIG (without multiple parton interactions). As expected, the "leading jet" and "back-to-back" events behave quite differently. For the "leading jet" case the densities rise with increasing P_T(jet#1), while for the "back-to-back" case they fall slightly with increasing P_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 does a better job describing the data than HERWIG. PYTHIA Tune A was determined by fitting the CDF Run 1 "underlying event" data [6].

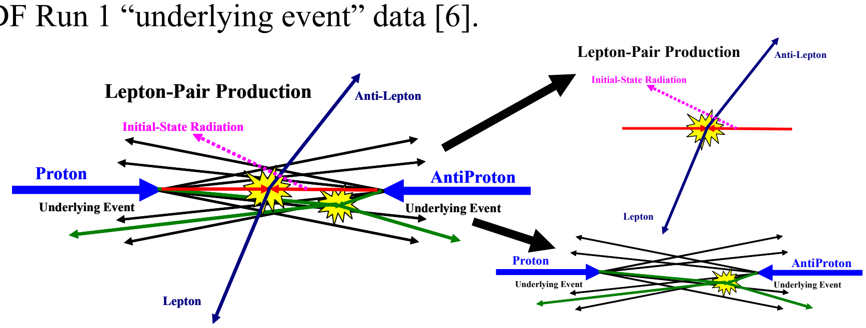

Fig. 4. Illustration of the way QCD Monte-Carlo models simulate Drell-Yan lepton-pair production. The "hard scattering" component of the event consists of the two outgoing leptons plus particles that result from initial-state radiation. The "underlying event" consists of particles that arise from the "beam-beam remnants" and from multiple parton interactions.

As illustrated in Fig. 4, Drell-Yan lepton-pair production provides an excellent place to study the underlying event. Here one studies the outgoing charged particles (excluding the lepton pair) as a function of the lepton-pair invariant mass. After removing the lepton-pair everything else results from the beam-beam remnants, multiple parton interactions, and initial-state radiation. Unlike high p_T jet production (Fig. 1) for lepton-pair production there is no final-state gluon radiation.

Fig. 5 shows that PYTHIA Tune A does not fit the CDF Run 1 Z-boson p_T distribution [7]. PYTHIA Tune A was determined by fitting the Run 1 "underlying event" data and, at that time, we did not consider the Z-boson data. PYTHIA Tune AW fits the Z-boson p_T distribution as well as the "underlying event" at the Tevatron [8]. PYTHIA Tune DW is very similar to Tune AW except PARP(67) = 2.5, which is the preferred value determined by DØ in fitting their dijet $\Delta\phi$ distribution [9]. It determines the maximal parton virtuality allowed in time-like showers. HERWIG does a fairly good job fitting the Z-boson p_T distribution without additional tuning, but does not fit the CDF "underlying event" data.

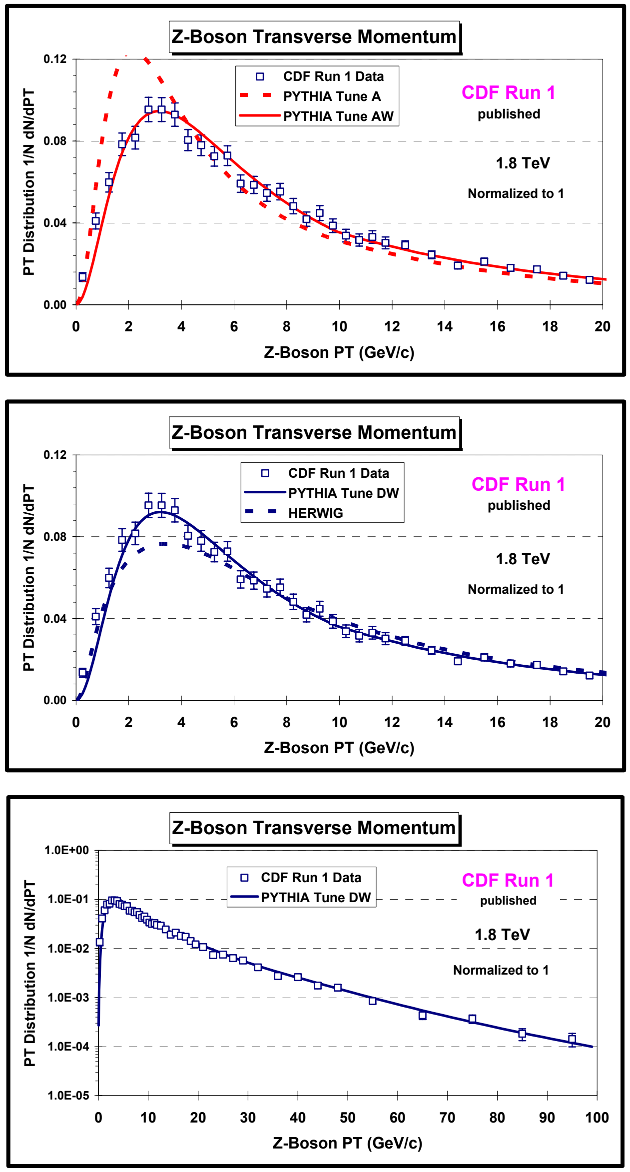

Fig. 5. CDF Run 1 data on the Z-boson p_T distribution compared with PYTHIA Tune A, Tune AW, Tune DW, and HERWIG.

Table 1 shows the parameters for several PYTHIA 6.2 tunes. Tune BW is a tune with PARP(67) = 1.0. Tune DW and Tune DWT are identical at 1.96 TeV, but Tune DW and DWT extrapolate differently to the LHC. Tune DWT uses the ATLAS energy dependence, PARP(90) = 0.16, while Tune DW uses the Tune A value of PARP(90) = 0.25. The ATLAS Tune is the default tune currently used by ATLAS at the LHC. The first 9 parameters in Table 5.1 tune the multiple parton interactions (MPI). PARP(62), PARP(64), and PARP(67) tune the initial-state radiation and the last three parameters set the intrensic k_T of the partons within the incoming proton and antiproton.

All the tunes except Tune QW use CTEQ5L. Tune QW uses CTEQ6.1 which is a next-to-leading order structure function. However, Tune QW uses leading order QCD coupling, α_s, with Λ = 0.192 GeV. Note that Tune QW has a much smaller value of PARP(82) (*i.e.* the MPI cut-off). This is due to the change in the low x gluon distribution in going from CTEQ5L to CTEQ6.1. Table 2 shows the computed value of the multiple parton scattering cross section for the various tunes. The multiple parton scattering cross section (divided by the total inelastic cross section) determines the average number of multiple parton collisions per event.

Table 1. Parameters for several PYTHIA 6.2 tunes. Tune A is a CDF Run 1 "underlying event" tune. Tune AW, DW, DWT, and BW are CDF Run 2 tunes which fit the existing Run 2 "underlying event" data and fit the Run 1 Z-boson p_T distribution. Tune QW is vary similar to Tune DW except that it uses the next-to-leading order structure function CTEQ6.1. The ATLAS Tune is the default tune currently used by ATLAS at the LHC. The first 9 parameters tune the multiple parton interactions. PARP(62), PARP(62), and PARP(62) tune the initial-state radiation and the last three parameters set the intrensic k_T of the partons within the incoming proton and antiproton.

Parameter	Tune A	Tune AW	Tune DW	Tune DWT	Tune BW	ATLAS	Tune QW
PDF	CTEQ5L	CTEQ5L	CTEQ5L	CTEQ5L	CTEQ5L	CTEQ5L	CTEQ6.1
MSTP(81)	1	1	1	1	1	1	1
MSTP(82)	4	4	4	4	4	4	4
PARP(82)	2.0	2.0	1.9	1.9409	1.8	1.8	1.1
PARP(83)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4	0.4	0.4	0.5	0.4
PARP(85)	0.9	0.9	1.0	1.0	1.0	0.33	1.0
PARP(86)	0.95	0.95	1.0	1.0	1.0	0.66	1.0
PARP(89)	1800	1800	1800	1960	1800	1000	1800
PARP(90)	0.25	0.25	0.25	0.16	0.25	0.16	0.25
PARP(62)	1.0	1.25	1.25	1.25	1.25	1.0	1.25
PARP(64)	1.0	0.2	0.2	0.2	0.2	1.0	0.2
PARP(67)	4.0	4.0	2.5	2.5	1.0	1.0	2.5
MSTP(91)	1	1	1	1	1	1	1
PARP(91)	1.0	2.1	2.1	2.1	2.1	1.0	2.1
PARP(93)	5.0	15.0	15.0	15.0	15.0	5.0	15.0

Table 2. Shows the computed value of the multiple parton scattering cross section for the various PYTHIA 6.2 tunes.

Tune	σ(MPI) at 1.96 TeV	σ(MPI) at 14 TeV
A, AW	309.7 mb	484.0 mb
DW	351.7 mb	549.2 mb
DWT	351.7 mb	829.1 mb
BW	401.7 mb	624.8 mb
QW	296.5 mb	568.7 mb
ATLAS	324.5 mb	768.0 mb

As can be seen in Figs. 6 – 8, PYTHIA Tune A, AW, DW, DW, and QW have been adjusted to give similar results for the charged particle density and the PTsum density in the "transverse" region with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events at 1.96 TeV. PHYTIA Tune A fits the CDF Run 2 "underlying event" data for "leading jet" events and Tune AW, BW, DW, and QW roughly agree with Tune A. Fig. 9 shows that PYTHIA Tune A, Tune DW, and the ATLAS PYTHIA Tune predict about the same density of charged particles in the "transverse" region with $p_T > 0.5$ GeV/c for "leading jet" events at the Tevatron. However, the ATLAS Tune has a much softer p_T distribution of charged particles resulting in a much smaller average p_T per particles. Fig. 9 shows that the softer p_T distribution of the ATLAS Tune does not agree with the CDF data.

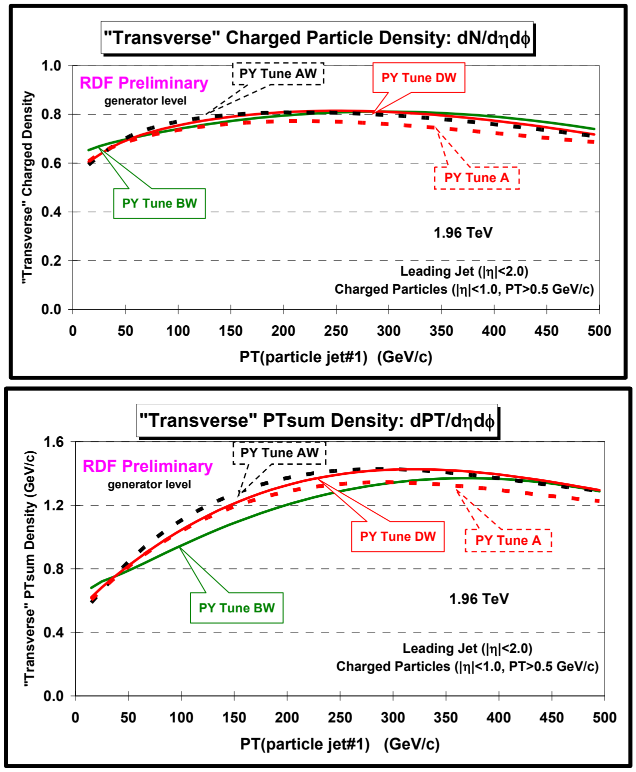

Fig. 6. Predictions at 1.96 TeV of PYTHIA Tune A, Tune AW, Tune BW, and Tune DW for the density of charged particles, dN/dηdφ (*top*), and the charged PTsum density, dPT/dηdφ (*bottom*), with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events as a function of the leading jet P_T.

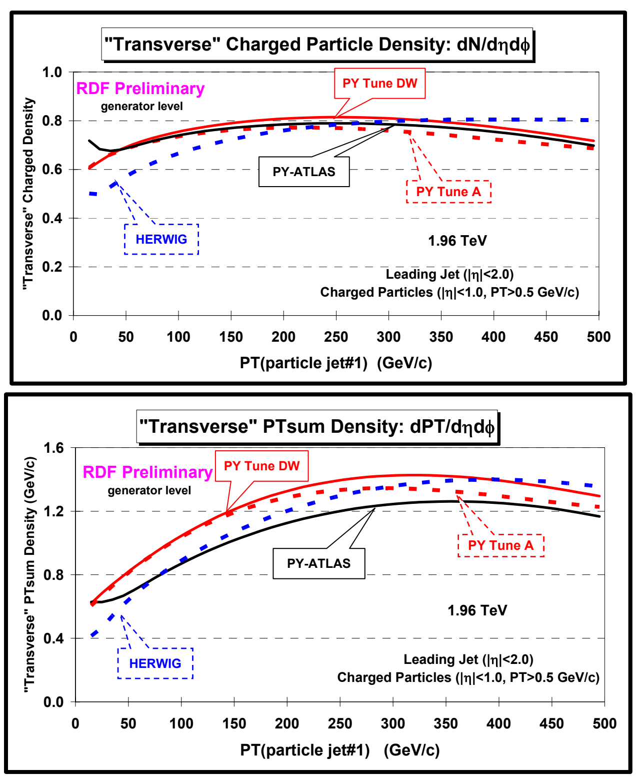

Fig. 7. Predictions at 1.96 TeV of PYTHIA Tune DW (DWT), HERWIG, and the ATLAS Tune for the density of charged particles, dN/dηdφ (*top*), and the charged PTsum density, dPT/dηdφ (*bottom*), with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events as a function of the leading jet P_T. Tune DW and DWT are identical at 1.96 TeV.

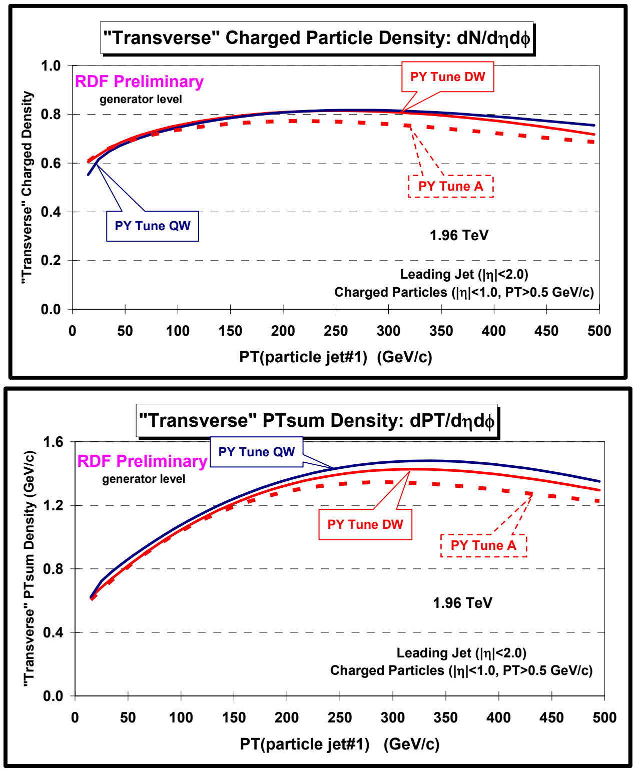

Fig. 8. Predictions at 1.96 TeV of PYTHIA Tune A, Tune DW, and Tune QW for the density of charged particles, dN/dηdϕ (*top*), and the charged PTsum density, dPT/dηdϕ (*bottom*), with p_T > 0.5 GeV/c and |η| < 1 in the "transverse" region for "leading jet" events as a function of the leading jet P_T.

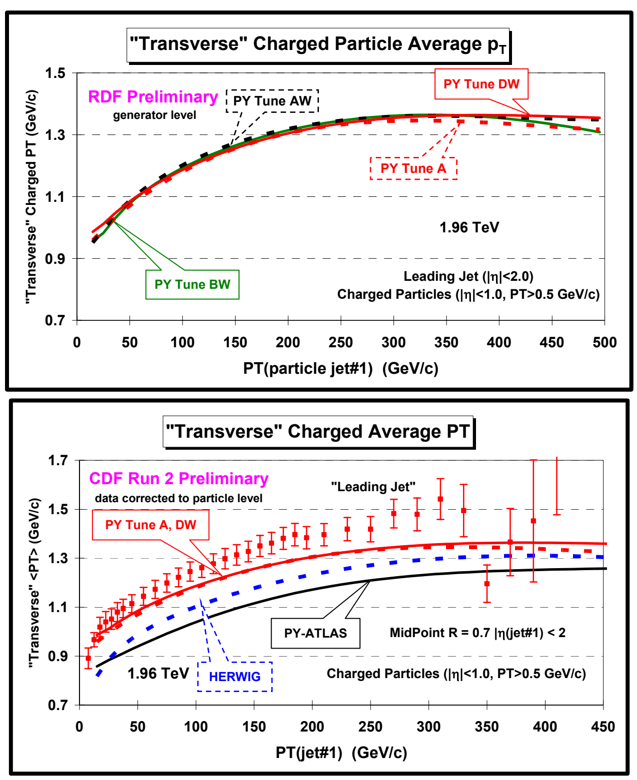

Fig. 9. (*top*) Predictions of PYTHIA Tune A, Tune AW, Tune BW, and Tune DW for average p_T of charged particles with p_T > 0.5 GeV/c and |η| < 1 in the "transverse" region for "leading jet" events at 1.96 TeV as a function of the leading jet P_T. (*bottom*) CDF Run 2 data at 1.96 TeV on the average p_T of charged particles with p_T

> 0.5 GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events as a function of the leading jet P_T compared with PYTHIA Tune A, Tune DW, HERWIG, and the ATLAS PYTHIA Tune.

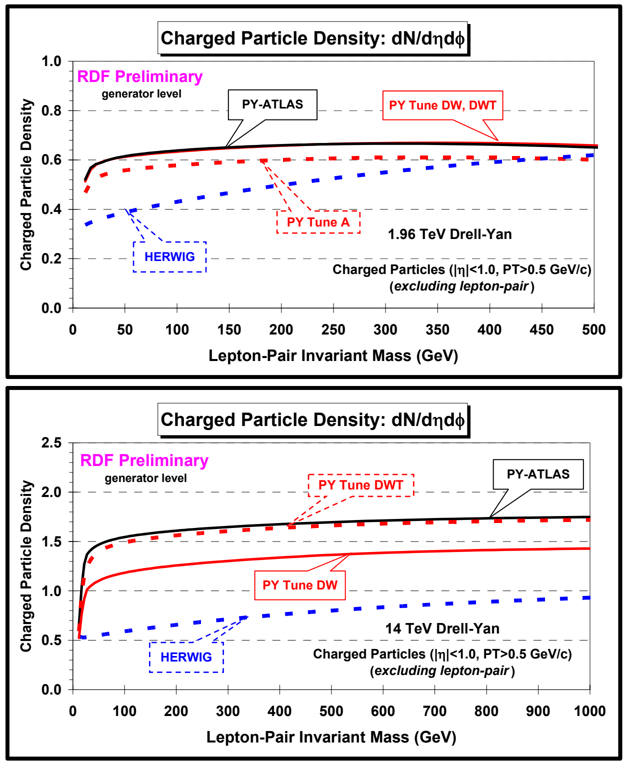

Fig. 10. Predictions of PYTHIA Tune A, Tune DW, Tune DWT, HERWIG, and the ATLAS PYTHIA Tune for the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in Drell-Yan lepton-pair production (excluding the lepton-pair) at 1.96 TeV (*top*) and 14 TeV (*bottom*) as a function of the invariant mass of the lepton pair. Tune DW and Tune DWT are identical at 1.96 TeV.

The predictions of PYTHIA Tune A, Tune DW, Tune DWT, HERWIG, and the ATLAS PYTHIA Tune for the density of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for Drell-Yan lepton-pair production at 1.96 TeV and 14 TeV are shown in Fig. 10. The ATLAS Tune and Tune DW predict about the same charged particle density with $p_T > 0.5$ GeV/c at the Tevatron, and the ATLAS Tune and Tune DWT predict about the same charged particle density with $p_T > 0.5$ GeV/c at the LHC. However, the ATLAS Tune has a much softer p_T distribution of particles, both at the Tevatron and the LHC. We are working to compare the CDF Run 2 data on Drell-Yan production with the QCD Monte-Carlo models and hope to have results soon.

Fig. 11 shows the predictions of PYTHIA Tune DW, Tune DWT, HERWIG, and the ATLAS Tune for the density of charged particles and the PTsum density in the "transverse" region for "leading jet" production at the LHC. The PYTHIA Tunes (with multiple parton interactions) predict a large increase in the charged particle density in going from the Tevatron (Fig. 7) to the LHC (Fig. 11). HERWIG (without multiple parton interactions) does not increase as much. PYTHIA Tune DWT and the ATLAS Tune both predict about the same charged particle density with $p_T > 0.5$ GeV/c, however, the ATLAS Tune predicts a smaller PTsum density than Tune DWT (*i.e.* the ATLAS Tune produces a softer p_T distribution).

The increased amount of initial-state radiation at the LHC results in a broader lepton-pair p_T distribution compared to the Tevatron. As can be seen in Fig. 12, even at the Z-boson mass the lepton-pair p_T distribution is predicted to be much broader at the LHC. This is indirectly related to the underlying event. More initial-state radiation results in a more active underlying event.

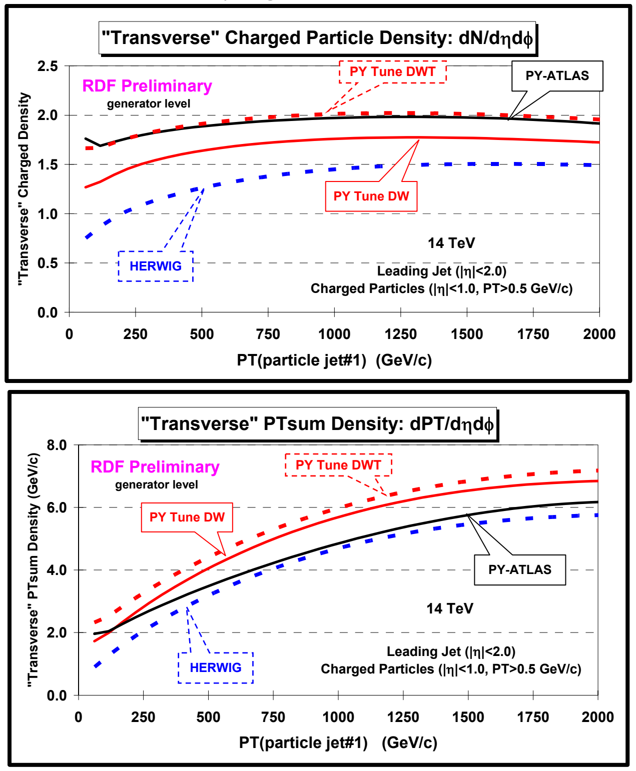

Fig. 11. Predictions at 14 TeV of PYTHIA Tune DW, Tune DWT, HERWIG, and the ATLAS Tune for the density of charged particles, $dN/d\eta d\phi$ (*top*), and the charged PTsum density, $dPT/d\eta d\phi$ (*bottom*), with $p_T > 0.5$ GeV/c and $|\eta| < 1$ in the "transverse" region for "leading jet" events as a function of the leading jet P_T.

Fig 13 shows the predictions at 14 TeV of PYTHIA Tune DW, Tune DWT, HERWIG, and the ATLAS Tune for the density of charged particles with $|\eta| < 1$ and $p_T > 0.5$ GeV/c and $p_T > 0.9$ GeV/c for Drell-Yan lepton-pair production (excluding the lepton-pair) as a function of the lepton-pair invariant mass. The ratio of the two p_T thresholds clearly shows that the ATLAS tune is has a much softer p_T distribution than the CDF tunes. We do not know what to expect at the LHC. For now I prefer PYTHIA Tune DW or Tune DWT over the ATLAS Tune because these tunes fit the CDF Run 2 data much better than the ATLAS Tune.

In my opinion the best PYTHIA 6.2 tune at present is Tune DW or DWT. These tunes are identical at the 1.96 TeV and they do a good job fitting the CDF Run 2 "underlying event" data. I expect they will do a good job in describing the underlying event in Drell-Yan lepton-pair production at the Tevatron (but we will have to wait for the data). More work will have to be done in studying the "universality" of these tunes. For example, we do not know if Tune DW will correctly describe the underlying event in top quark production. Tune QW (or the corresponding Tune QWT) is vary similar to Tune DW (or Tune DWT) except that it uses the next-to-leading order structure function CTEQ6.1. Many Monte-Carlo based analyses use the 40 error PDF's associated with CTEQ6.1 and it is useful to have a tune using the central fit (*i.e.* CTEQ6.1).

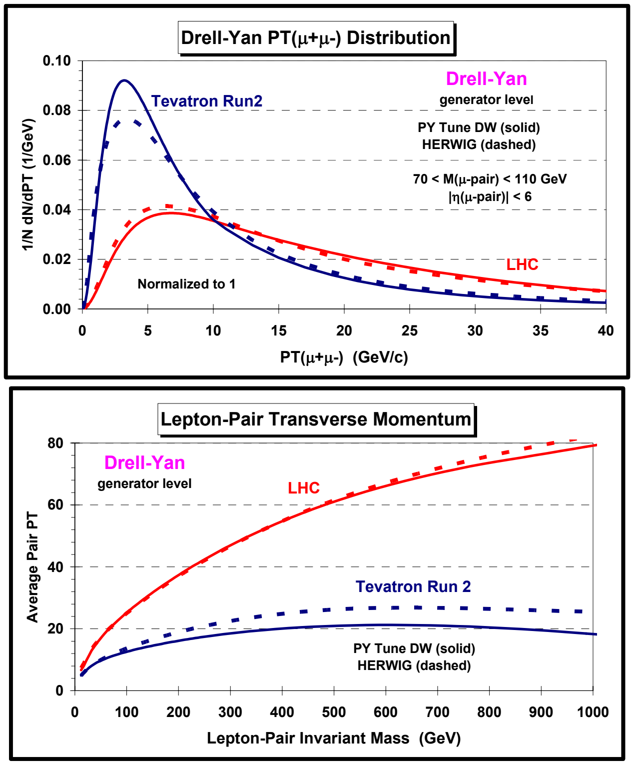

Fig. 12. Predictions at 1.96 TeV (Tevatron Run 2) and 14 TeV (LHC) of PYTHIA Tune DW and HERWIG for (*top*) the lepton-pair p_T distribution at the Z-boson mass and (*bottom*) the average lepton-pair p_T versus the lepton pair invariant mass.

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8. The value of PARP(62), PARP(64), and PARP(91) was determined by CDF Electroweak Group. The "W" in Tune AW, BW, DW, DWT, QW stands for "Willis". I combined the "Willis" tune with Tune A, etc..
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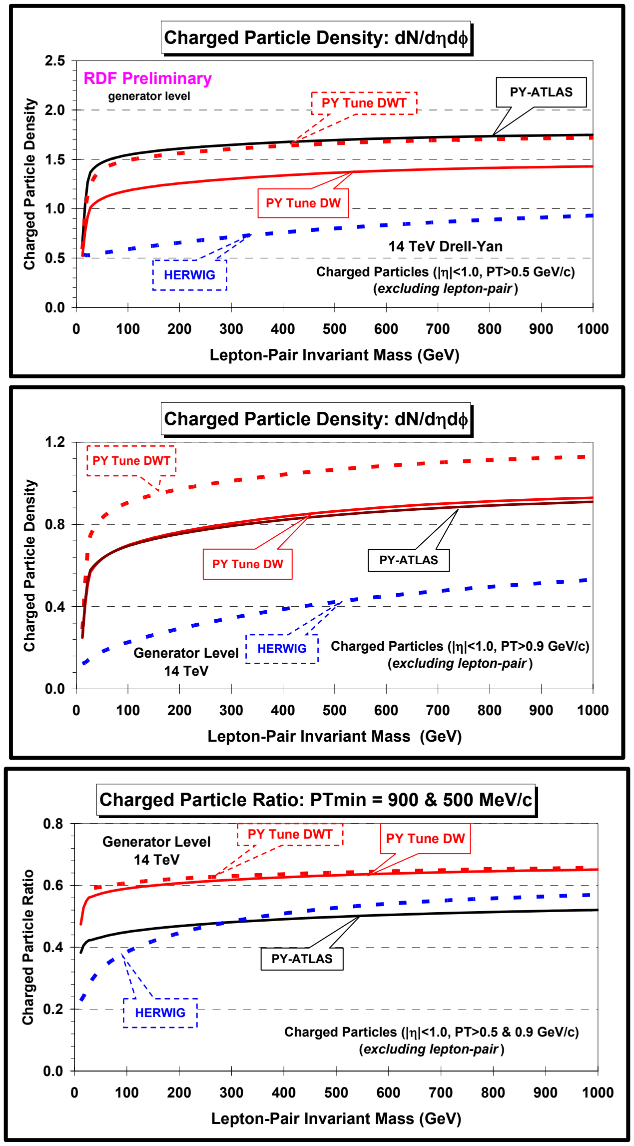

Fig. 13. Predictions at 14 TeV of PYTHIA Tune DW, Tune DWT, HERWIG, and the ATLAS Tune for the density of charged particles, dN/dηdφ, with $|\eta| < 1$ and $p_T > 0.5$ GeV/c (*top*) and $p_T > 0.9$ GeV/c (*middle*) for Drell-Yan lepton-pair production (excluding the lepton-pair) as a function of the lepton-pair invariant mass. (*bottom*) The ratio of the charged particle density with $p_T > 0.9$ GeV/c and $p_T > 0.5$ GeV/c.