

MIN-BIAS AND THE UNDERLYING EVENT AT THE LHC*

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In a very short time the experiments at the LHC have collected a large amount of data that can be used to study minimum bias (MB) collisions and the underlying event (UE) in great detail. The CDF PYTHIA 6.2 Tune DW predictions for the LHC UE data at 900 GeV and 7 TeV are examined in detail. The behavior of the UE at the LHC is roughly what we expected. The LHC PYTHIA 6.4 Tune Z1 does an excellent job describing the LHC UE data. The modeling of MB (*i.e.* the overall inelastic cross-section) is more complicated because one must include a model of diffraction. The ability of PYTHIA Tune DW and Tune Z1 to simultaneously describe both the UE in a hard scattering process and MB collisions are studied. No model describes perfectly all the features of MB collisions at the LHC.

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1. Introduction

The total proton–proton cross-section is the sum of the elastic and inelastic components, $\sigma_{\text{tot}} = \sigma_{\text{EL}} + \sigma_{\text{INEL}}$. Three distinct processes contribute to the inelastic cross-section: single diffraction, double-diffraction, and everything else, which is referred to as the “non-diffractive” (ND) component. For elastic scattering neither of the beam particles breaks apart (*i.e.* color singlet exchange). For single and double diffraction one or both of the beam particles are excited into a high mass color singlet state (*i.e.* N^* states) which then decays. Single and double diffraction also corresponds to color singlet exchange between the beam hadrons. When color is exchanged the outgoing remnants are no longer color singlets and one has a separation of color resulting in a multitude of quark–antiquark pairs being pulled out of

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the vacuum. The non-diffractive component, σ_{ND} , involves color exchange and the separation of color. However, the non-diffractive collisions have both a soft and hard component. Most of the time the color exchange between partons in the beam hadrons occurs through a soft interaction (*i.e.* no high transverse momentum) and the two beam hadrons “ooze” through each other producing lots of soft particles with a uniform distribution in rapidity and many particles flying down the beam pipe. Occasionally, there is a hard scattering among the constituent partons producing outgoing particles and “jets” with high transverse momentum.

Min-bias (MB) is a generic term which refers to events that are selected with a “loose” trigger that accepts a large fraction of the overall inelastic cross-section. All triggers produce some bias and the term “min-bias” is meaningless until one specifies the precise trigger used to collect the data. The underlying event (UE) consists of particles such as the beam–beam remnants (BBR) and the multiple parton interactions (MPI) that accompany a hard scattering. The UE is an unavoidable background to hard-scattering collider events. MB and UE are not the same object! The majority of MB collisions are soft while the UE is studied in events in which a hard-scattering has occurred. One uses the “jet” structure of the hard hadron–hadron collision to experimentally study the UE [1]. As shown in Fig. 1, on an event-by-event bases, the leading charged particle, PTmax, or the leading charged particle jet, chgjet#1, can be used to isolate regions of η – ϕ space that are

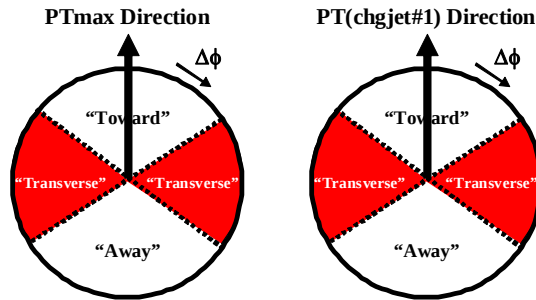


Fig. 1. Illustration of correlations in azimuthal angle $\Delta\phi$ relative to (left) the direction of the leading charged particle, PTmax, or to (right) the leading charged particle jet, chgjet#1. The relative angle $\Delta\phi = \phi - \phi_1$, where ϕ_1 is the azimuthal angle of PTmax (or chgjet#1) and ϕ is the azimuthal angle of a charged particle. There are two “transverse” regions $60^\circ < \Delta\phi < 120^\circ$, $|\eta| < \eta_{\text{cut}}$ and $60^\circ < -\Delta\phi < 120^\circ$, $|\eta| < \eta_{\text{cut}}$. The overall “transverse” region of η – ϕ space is defined by $60^\circ < |\Delta\phi| < 120^\circ$, $|\eta| < \eta_{\text{cut}}$. The “transverse” charged particle density is the number of charged particles in the “transverse” region divided by the area in η – ϕ space. Similarly, the “transverse” charged PTsum density is the scalar PTsum of charged particles in the “transverse” region divided by the area in η – ϕ space.

very sensitive to the modeling of the UE. The pseudo-rapidity is defined by $\eta = -\log(\tan(\theta_{\text{cm}}/2))$, where θ_{cm} is the center-of-mass polar scattering angle and ϕ is the azimuthal angle of outgoing charged particles. In particular, the “transverse” region defined by $60^\circ < |\Delta\phi| < 120^\circ$, where $\Delta\phi = \phi - \phi_1$, where ϕ_1 is the azimuthal angle of PTmax (or chgjet#1) and ϕ is the azimuthal angle of a charged particle is roughly perpendicular to the plane of the hard 2-to-2 parton-parton scattering and is therefore very sensitive to the UE.

QCD Monte Carlo generators such as PYTHIA [2] have parameters which may be adjusted to control the behavior of their event modeling. A specified set of these parameters that has been adjusted to better fit some aspects of the data is referred to as a tune [3]. In Sec. 2 I will review briefly the CDF PYTHIA 6.2 tunes. PYTHIA Tune DW does a very nice job in describing the CDF Run 2 underlying event data. In Sec. 3 we will take a close look at how well PYTHIA Tune DW did at predicting the behavior of the UE at 900 GeV and 7 TeV at the LHC. We will see that Tune DW does a fairly good job in describing the LHC UE data. However, Tune DW does not reproduce perfectly all the features of the data and after seeing the data one can construct improved LHC UE tunes. The first ATLAS LHC tune was Tune AMBT1 [4] and CMS has Tune Z1 and Tune Z2 which I will discuss in Sec. 4. MB and the UE in a hard scattering process are not the same object, however, in PYTHIA the modeling of the UE and the modeling of the inelastic non-diffractive cross-section are related. In Sec. 5 we will examine how well the PYTHIA tunes fit the LHC MB data. The summary and conclusions are in Sec. 6.

2. Studying the UE at CDF

Figure 2 shows some of the first comparisons to come from the CDF UE studies [1]. The CDF Run 1 at 1.8 TeV on the density of charged particles in the “transverse” region as defined by the leading charged particle jet, chgjet#1, are compared with ISAJET 7.32 [5] (without MPI) and HERWIG 6.4 [6] (without MPI) using the ISAJET and HERWIG default parameters with $p_{\text{T}}(\text{hard}) > 3 \text{ GeV}/c$. The Monte Carlo predictions are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jets plus initial and final-state radiation (hard scattering component). HERWIG 6.4 has improved modeling of the parton showers (modified leading-log), whereas ISAJET simply uses the leading-log approximation. The modified leading-log takes into account the angle-ordering of the shower that is indicated by higher order corrections. Clearly, the hard-scattering component of HERWIG does a much better job in describing the data than

does the hard-scattering component of ISAJET. However, it became clear that the beam-beam remnants of HERWIG were too soft to describe the CDF Run 1 UE data. To describe the data one needs to include MPI.

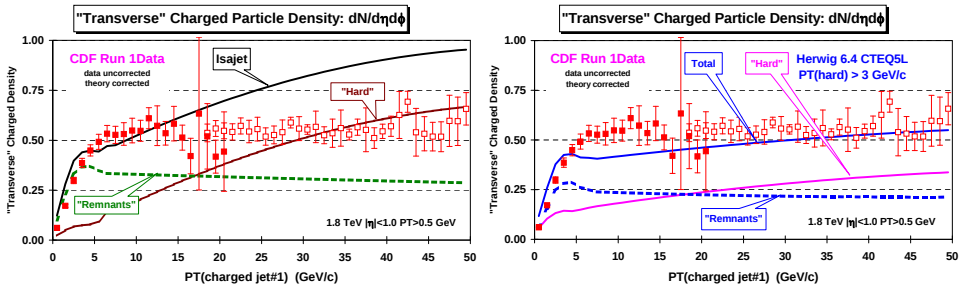


Fig. 2. CDF Run 1 data from Ref. [1] at 1.8 TeV on the density of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the “transverse” region as defined by the leading charged particle jet, chgjet#1, as a function of $P_T(\text{chgjet}\#1)$. The data are compared with ISAJET 7.32 without MPI (left) and HERWIG 6.4 without MPI (right) using the ISAJET and HERWIG default parameters with $p_T(\text{hard}) > 3$ GeV/c. The Monte Carlo predictions are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jets plus initial and final-state radiation (hard scattering component).

Figure 3 shows the first attempts to tune the parameters of PYTHIA 6.2 to fit the CDF Run 1 UE data and Table I give the value of the parameters for the some of the CDF tunes. The perturbative 2-to-2 parton-parton differential cross-section diverges like $1/\hat{p}_T^4$, where $\hat{p}_T$ is the transverse momentum of the outgoing parton in the parton-parton center-of-mass frame. PYTHIA regulates this cross-section by including a smooth cut-off p_{T0} as follows: $1/\hat{p}_T^4 \rightarrow 1/(\hat{p}_T^2 + p_{T0}^2)^2$. This approaches the perturbative result for large scales and is finite as $\hat{p}_T \rightarrow 0$. The primary hard scattering processes and the MPI are regulated in the same way with the one parameter $p_{T0} = \text{PARP}(82)$. This parameter governs the amount of MPI in the event. Smaller values of p_{T0} result in more MPI due to a larger MPI cross-section. $\text{PARP}(67)$ sets the high p_T scale for initial-state radiation in PYTHIA 6.2. It determines the maximal parton virtuality allowed in time-like showers. The larger the value of $\text{PARP}(67)$ the more initial-state radiation in the event. Tune A has more initial-state radiation and less MPI and Tune B has less initial-state radiation and slightly more MPI. However, as can be seen in Fig. 3 one cannot discriminate between them by simply looking at the activity in the “transverse” region.

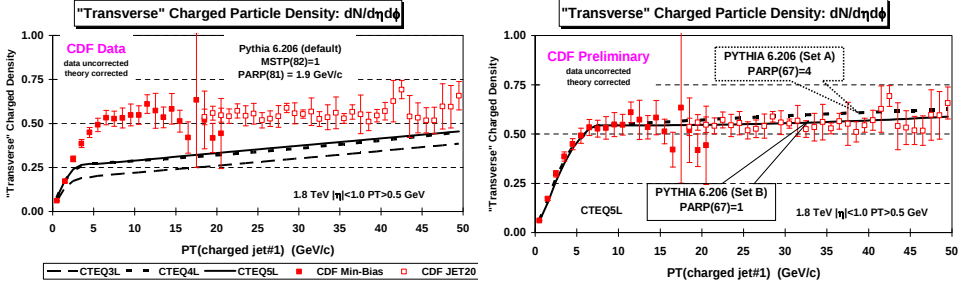


Fig. 3. CDF Run 1 data from Ref. [1] at 1.8 TeV on the density of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, as a function of $P_T(\text{chgjet}\#1)$. The data are compared with PYTHIA 6.206 with MPI (left) using the PYTHIA default parameters with $p_T(\text{hard}) \geq 0$ with the CTEQ3L, CTEQ4L, and CTEQ5L parton distribution functions. (right) Two CDF PYTHIA 6.2 tunes, Tune A and Tune B. Tune A was adjusted to fit the CDF Run 1 data with $\text{PARP}(67) = 4.0$ and Tune B was adjusted to fit the same data but with $\text{PARP}(67) = 1.0$.

TABLE I

Parameters for several PYTHIA 6.2 tunes. Tune A and Tune B are CDF Run 1 UE tunes. Tune DW, D6, and DWT are CDF Run 2 tunes which fit the Run 2 UE data and fit the Run 1 Z -boson p_T distribution. Tune DW and Tune DWT are identical at 1.96 TeV but have a different energy dependence. Tune D6 is similar to Tune DW but uses CTEQ6L.

Parameter	Tune A	Tune B	Tune DW	Tune D6	Tune DWT
PDF	CTEQ5L	CTEQ5L	CTEQ5L	CTEQ6L	CTEQ5L
MSTP(81)	1	1	1	1	1
MSTP(82)	4	4	4	4	4
PARP(82)	2.0	1.9	1.9	1.8	1.9409
PARP(83)	0.5	0.5	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4	0.4	0.4
PARP(85)	0.9	0.9	1.0	1.0	1.0
PARP(86)	0.95	0.95	1.0	1.0	1.0
PARP(89)	1800	1800	1800	1800	1960
PARP(90)	0.25	0.25	0.25	0.25	0.16
PARP(62)	1.0	1.0	1.25	1.25	1.25
PARP(64)	1.0	1.0	0.2	0.2	0.2
PARP(67)	4.0	1.0	2.5	2.5	2.5
MSTP(91)	1	1	1	1	1
PARP(91)	1.0	1.0	2.1	2.1	2.1
PARP(93)	5.0	5.0	15.0	15.0	15.0

These CDF studies indicated that p_{T0} is around 2 GeV/c at 1.96 TeV. However, this cut-off is expected depend on the center-of-mass energy of the hadron-hadron collision, E_{cm} . PYTHIA parameterizes this energy dependence as follows: $p_{T0}(E_{\text{cm}}) = (E_{\text{cm}}/E_0)^\epsilon$, where $E_0 = \text{PARP}(89)$ is the reference energy and the parameter $\epsilon = \text{PARP}(90)$ determines the energy dependence. Figure 4 shows how the $\text{PARP}(90)$ parameter for Tune A was determined. I determined the value of $\epsilon = 0.25$ by comparing the UE activity in the CDF data at 1.8 TeV and 630 GeV [7].

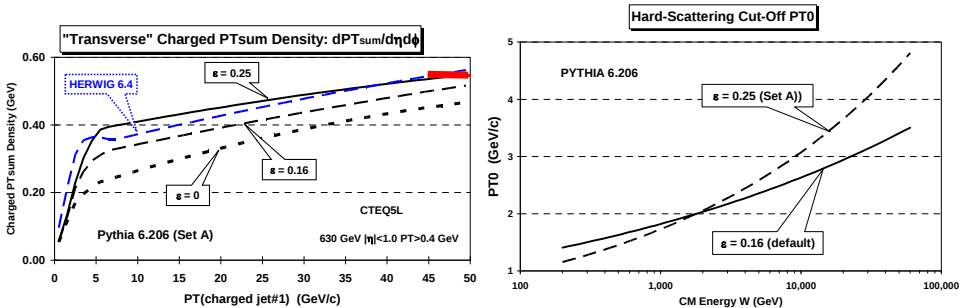


Fig. 4. (left) PYTHIA Tune A predictions at 630 GeV for the charged PTsum density ($p_T > 0.4$ GeV/c, $|\eta| < 1$) in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, as a function of $P_T(\text{chgjet}\#1)$ with $\epsilon = \text{PARP}(90) = 0.0, 0.16$ (default), and 0.25 . The CDF Run 1 data at 630 GeV from Ref. [7] indicated a value of the PTsum density of around 0.54 GeV/c at $P_T(\text{chgjet}\#1) \approx 50$ GeV/c (thick grey (red) line) which favors the $\text{PARP}(90) = 0.25$ curve. (right) Shows the 2-to-2 hard scattering cut-off, p_{T0} , versus center-of-mass energy from PYTHIA Tune A with the default value $\text{PARP}(90) = 0.16$ and the Tune A value of $\text{PARP}(90) = 0.25$.

Figure 5 shows that Tune A does not fit the CDF Run 1 Z -boson p_T distribution very well [8]. PYTHIA Tune AW was adjusted to fit the Z -boson p_T distribution as well as the underlying event at the Tevatron. The UE activity of Tune A and Tune AW are nearly identical. PYTHIA Tune DW is very similar to Tune AW except Tune DW has $\text{PARP}(67) = 2.5$, which is the preferred value determined by the D0 Collaboration in fitting their dijet $\Delta\phi$ distribution [9].

The MPI tune depends on the choice of parton distribution function (PDF). One must choose a PDF and then tune to fit the UE. Tune A, B, AW, and DW use CTEQ5L. Tune D6 is similar to tune DW except it uses CTEQ6L as the PDF. Note that in changing from CTEQ5L to CTEQ6L, $p_{T0} = \text{PARP}(82)$ decreased by a factor of $1.8/1.9 \approx 0.95$ in order to get the same UE activity.

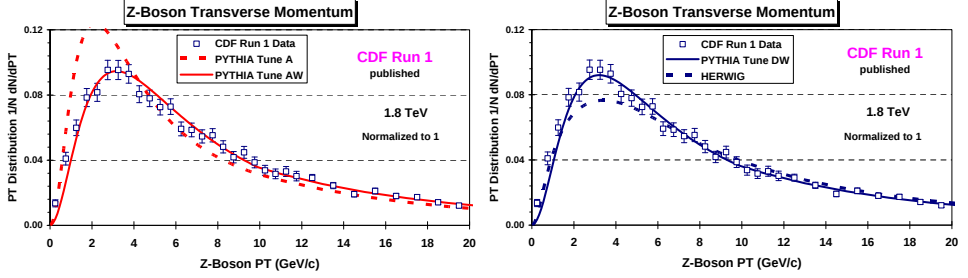


Fig. 5. The CDF Run 1 data from Ref. [8] on the Z -boson p_T distribution ($\langle p_T(Z) \rangle \approx 11.5$ GeV/c) compared with (left) PYTHIA Tune A ($\langle p_T(Z) \rangle = 9.7$ GeV/c) and PYTHIA Tune AW ($\langle p_T(Z) \rangle = 11.7$ GeV/c) and compared with (right) PYTHIA Tune DW and HERWIG 6.4 (without MPI).

PYTHIA Tune A, AW, DW, and D6 use $\epsilon = \text{PARP}(90) = 0.25$, which is much different than the PYTHIA 6.2 default value of 0.16. Tune DWT uses the default value of 0.16. Tune DW and Tune DWT are identical at 1.96 TeV, but Tune DW and DWT extrapolate to other energies differently. Tune DWT produces more activity in the UE at energies above the Tevatron than does Tune DW, but predicts less activity than Tune DW in the UE at energies below the Tevatron as shown in Fig. 6. The data from the STAR Collaboration at 0.2 TeV at RHIC [10] favor the energy dependence of Tune DW and rule out the energy dependence of Tune DWT.

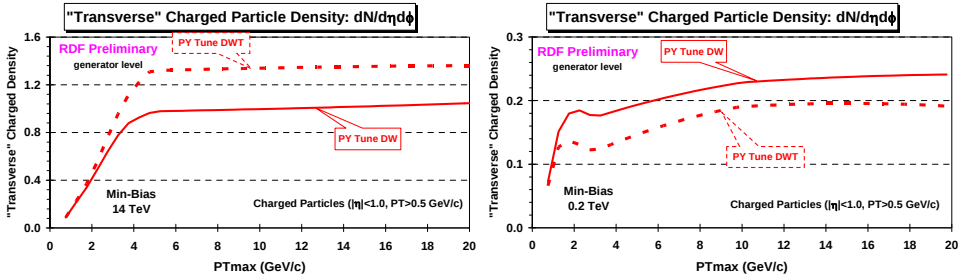


Fig. 6. Shows the charged particle density in the “transverse” region as defined by the leading charged particle, PT_{max} , as function of PT_{max} for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ at 0.2 TeV and 14 TeV from PYTHIA Tune DW and Tune DWT at the particle level. The STAR data from RHIC [10] favored the energy dependence of Tune DW.

Figure 7 shows the extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC (14 TeV). Tune pyATLAS is the original ATLAS tune that used the default parameter of $\text{PARP}(90) = 0.16$. Both Tune DWT and the old pyATLAS tune

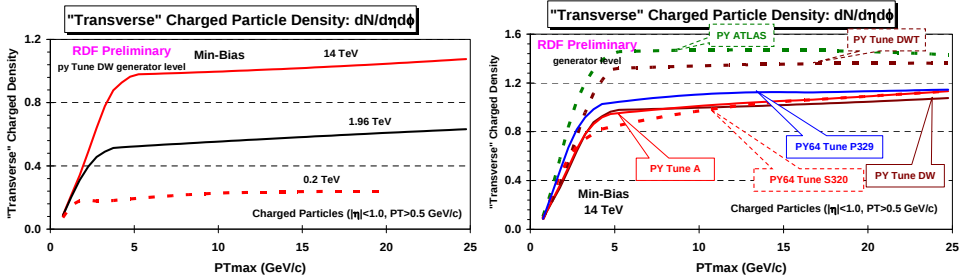


Fig. 7. (left) Shows the predictions at the particle level of PYTHIA Tune DW for the charged particle density in the “transverse” region as defined by the leading charged particle, PT_{max} , as a function of PT_{max} for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) at 0.2 TeV, 1.96 TeV and 14 TeV. (right) Shows the extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC at 14 TeV.

are ruled out by the RHIC UE data. Tune S320 is the original Perugia0 tune from Skands [3] and Tune P329 is a “professor” tune from Hendrik Hoeth. In November of 2009 Tune DW, Tune S320, and Tune P329 seemed to be converging on the same predictions for the LHC. I began to feel that we could make accurate LHC predictions with some confidence. Figure 8 shows the charged particle density in the “transverse” region at 7 TeV as

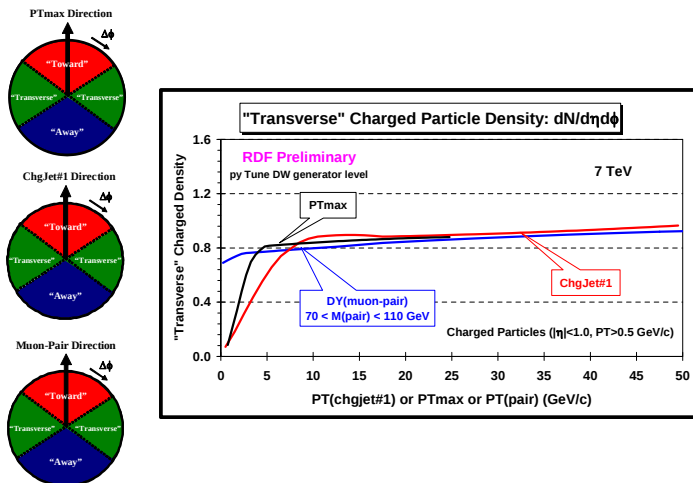


Fig. 8. Shows the charged particle density in the “transverse” region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) at 7 TeV as defined by PT_{max} , $P_T(chgjet\#1)$, and $P_T(muon-pair)$ predicted from PYTHIA Tune DW at the particle level. For muon-pair production the two muons are excluded from the charged particle density. Charged particle jets are constructed using the Anti-KT algorithm with $d = 0.5$.

defined by P_{Tmax} , $chgjet\#1$, and the muon-pair in Drell–Yan production as predicted from PYTHIA Tune DW. The density of charged particles in the “transverse” region goes to zero as P_{Tmax} or $P_T(chgjet\#1)$ go to zero due to kinematics. If P_{Tmax} is equal to zero then there are no charged particles anywhere in the η region considered. Similarly for $P_T(chgjet\#1)$. However, if the $P_T(muon\text{-}pair)$ goes to zero there is still the hard scale of the mass of the muon-pair and, hence, the charge particle density is not zero at $P_T(muon\text{-}pair) = 0$.

Figure 9 shows the center-of-mass energy dependence of the charged particle density in the “transverse” region predicted by PYTHIA Tune DW. The height of the “plateau” in the “transverse” region does not increase linearly with the center-of-mass energy. For energies above the Tevatron it increases more like a straight line on a log plot (or a small power of E_{cm}). The UE activity is predicted by PYTHIA Tune DW to increase by about a factor of two in going from 900 GeV to 7 TeV and then to increase by only about 20% in going from 7 TeV to 14 TeV.

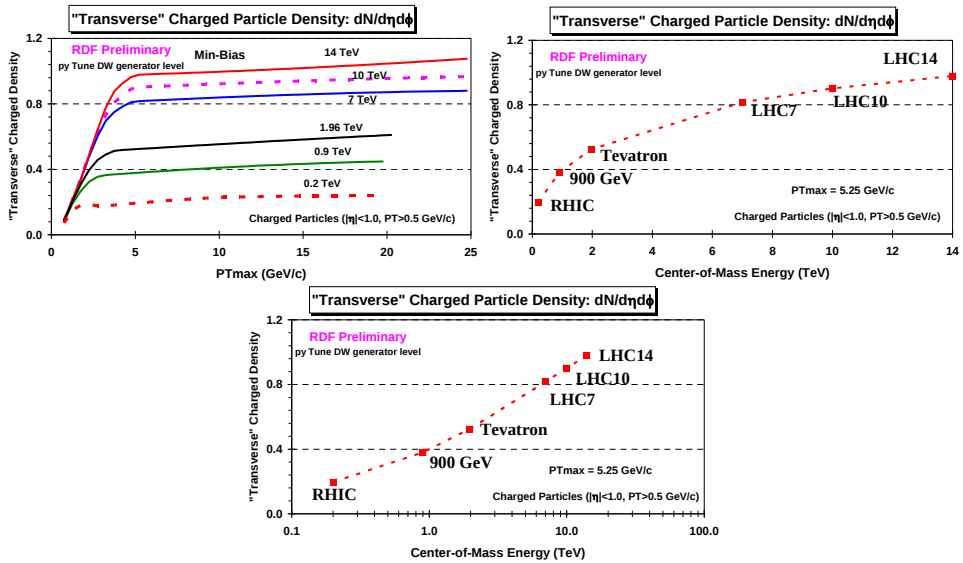


Fig. 9. (top left) Shows the charged particle density in the “transverse” region as defined by the leading charged particle, P_{Tmax} , a function of P_{Tmax} for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, and 14 TeV as predicted by PYTHIA Tune DW at the particle level. Also, shows the charged particle density in the “transverse” region as defined by the leading charged particle, P_{Tmax} , at $P_{Tmax} = 5.25$ GeV/c for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) as a function of the center-of-mass energy on a linear plot (top right) and a logarithmic plot (bottom).

3. PYTHIA 6.2 Tune DW and the LHC UE data

The left column of Fig. 10 shows two plots that I presented at the MB&UE CMS Workshop at CERN on November 6, 2009 before we had LHC data. The plots show generator level predictions of PYTHIA Tune DW at 900 GeV for the transverse charged particle density and the transverse charged PTsum density as defined by the leading charged particle (PTmax) and the leading charged particle jet ($P_T(\text{chgjet}\#1)$) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The plots also show fake data at 900 GeV generated from PYTHIA Tune DW assuming 500,000 MB events (361,595 events in the plot). The fake data agree perfectly with Tune DW since it was generated from Tune DW! This is what I expected the data to look like if CMS received 500,000 MB triggers at 900 GeV. The right column of

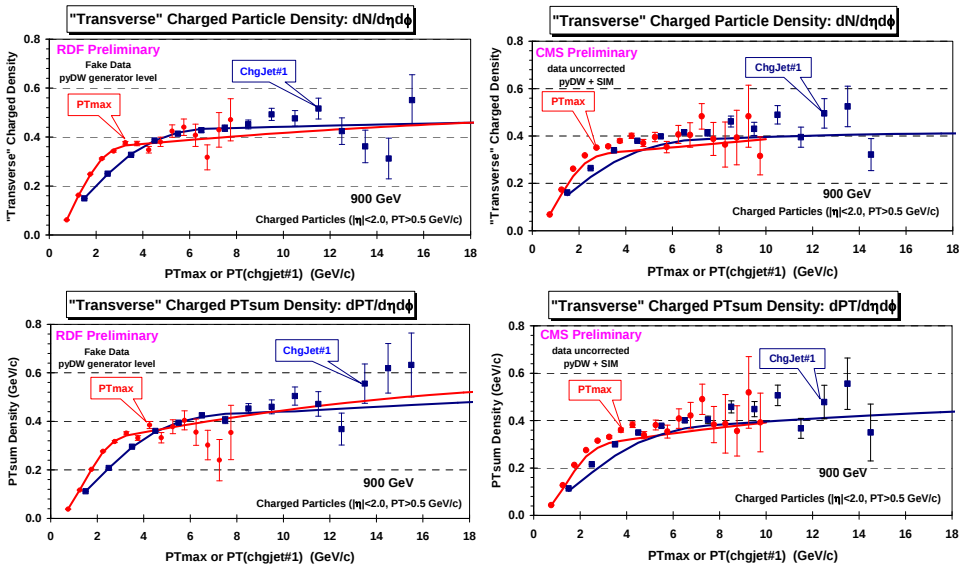


Fig. 10. (left column) Fake data at 900 GeV on the transverse charged particle density (top left) and the transverse charged PTsum density (bottom left) as defined by the leading charged particle (PTmax) and the leading charged particle jet ($P_T(\text{chgjet}\#1)$) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot). (right column) CMS data [11] at 900 GeV on the transverse charged particle density (top right) and the transverse charged PTsum density (bottom right) as defined by the leading charged particle (PTmax) and the leading charged particle jet ($P_T(\text{chgjet}\#1)$) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation (216,215 events in the plot).

Fig. 10 shows the data CMS collected at the LHC during the commissioning period of December 2009 [11]. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation (216,215 events in the plot). CMS did not quite get 500,000 MB triggers, but we got enough to get a first look at the underlying event activity at 900 GeV. PYTHIA Tune DW did a fairly good job in describing the features of this data, but it does not fit the data perfectly. It does not fit the real data quite as well as it fits the fake data! However, we saw roughly what we expected to see.

Figure 11 shows early CMS and ATLAS [12] data at 900 GeV and 7 TeV on the transverse charged particle density and the transverse charged PTsum density compared with the predictions of PYTHIA Tune DW. Here CMS used the leading charged particle jet (chgjet#1) to define the transverse region and ATLAS used the leading charged particle, PTmax. The ATLAS data are corrected to the particle level and compared with Tune DW at the generator level. The CMS data are uncorrected and compared with

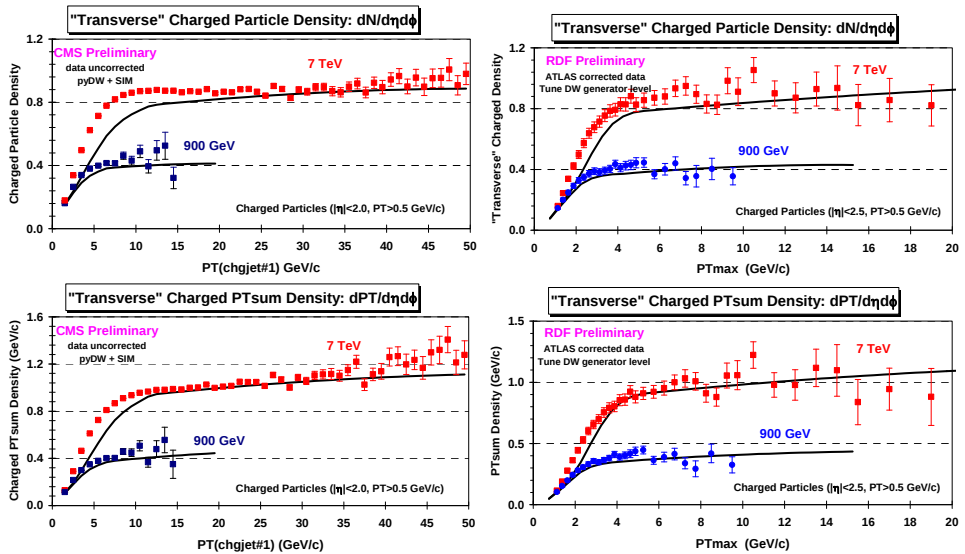


Fig. 11. (left column) Early CMS data at 900 GeV and 7 TeV on the transverse charged particle density (top left) and the transverse charged PTsum density (bottom left) as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation. (right column) ATLAS data [12] at 900 GeV and 7 TeV on the transverse charged particle density (top right) and the transverse charged PTsum density (bottom right) as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.

Tune DW after detector simulation (pyDW + SIM). Tune DW predicted about the right amount of activity in the “plateau”, but does not fit the low p_T rise very well.

Figure 12 shows early CMS and ATLAS data on the ratio between 7 TeV and 900 GeV (7 TeV divided by 900 GeV) for the transverse charged particle density and the transverse charged PTsum density compared with PYTHIA Tune DW. Tune DW predicted that the transverse charged particle density would increase by about a factor of two in going from 900 GeV to 7 TeV and that the transverse PTsum density would have a slightly larger increase. Both these predictions are seen in the data, although Tune DW does not fit very well the energy dependence of the low p_T approach to the “plateau”.

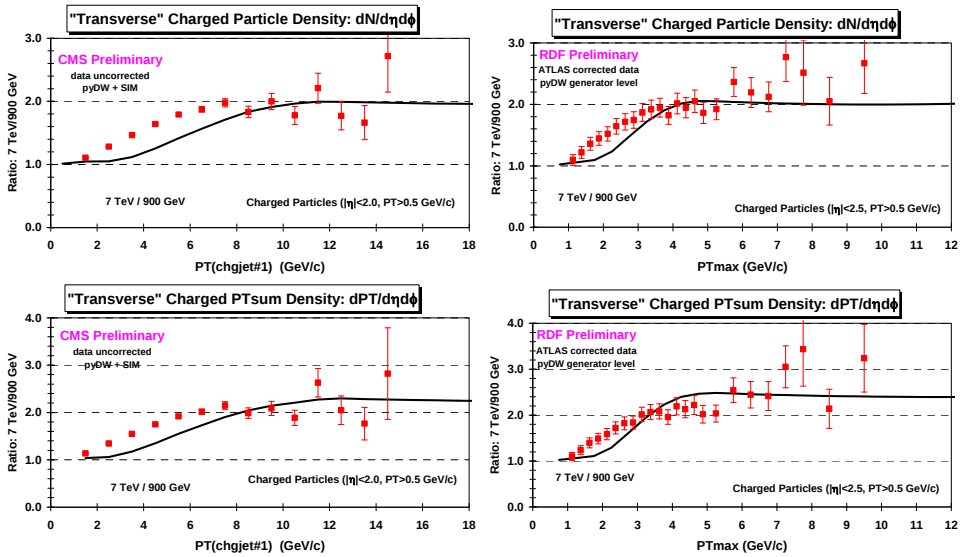


Fig. 12. (left column) Early CMS data on the ratio of 7 TeV and 900 GeV (7 TeV divided by 900 GeV from Fig. 11) for the transverse charged particle density (top left) and the transverse charged PTsum density (bottom left) as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation. (right column) ATLAS data on the ratio of 7 TeV and 900 GeV from Fig. 11 for the transverse charged particle density (top right) and the transverse charged PTsum density (bottom right) as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.

Figure 13 shows the CDF data at 1.96 TeV [13] on the charged particle density in the “transverse” region as defined by the leading calorimeter jet, jet#1, as a function of $P_T(\text{jet}\#1)$ together with the recent CMS data [14]

at 900 GeV and 7 TeV on the charged particle density in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, as a function of $P_T(\text{chgjet}\#1)$ compared with PYTHIA Tune DW. I would say that the agreement at all three energies is fairly good. Tune DW, however, is not a perfect fit to the LHC UE data. It does not fit the Tevatron data perfectly either! We expect a lot from the QCD Monte Carlo models. We want them to fit perfectly which is, of course, not always possible.

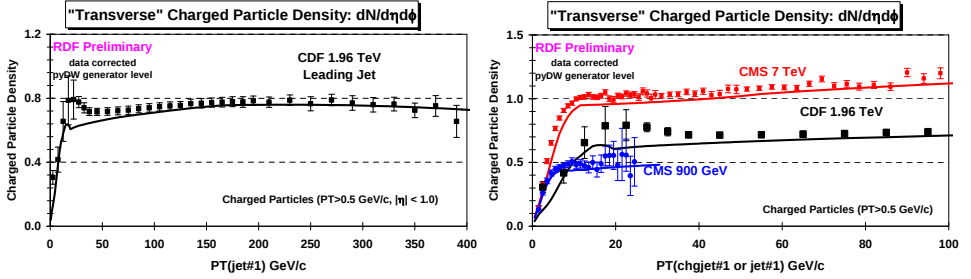


Fig. 13. (left) CDF data at 1.96 TeV from Ref. [13] on the charged particle density ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the “transverse” region as defined by the leading calorimeter jet, $\text{jet}\#1$, as a function of $P_T(\text{jet}\#1)$ compared with PYTHIA Tune DW. Also compares the CDF data at 1.96 TeV with the CMS data [14] at 900 GeV and 7 TeV (right) on the “transverse” charged particle density ($p_T > 0.5$ GeV/c, $|\eta| < 2$) in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, as a function of $P_T(\text{chgjet}\#1)$. The data are corrected to the particle level and compared with PYTHIA Tune DW at the generator level.

4. PYTHIA 6.4 CMS UE Tune Z1 and Tune Z2

Tune DW is a PYTHIA 6.2 tune (Q^2 -ordered parton showers, old MPI model) designed by me to fit the CDF underlying event data at 1.96 TeV. Now that we have LHC data at 900 GeV and 7 TeV both ATLAS and CMS have LHC tunes. The ATLAS Tune AMBT1 [4] is a PYTHIA 6.4 tune (p_T -ordered parton showers, new MPI model) designed to fit the ATLAS LHC MB data for $N_{\text{chg}} \geq 6$ and $p_T > 0.5$ GeV/c (*i.e.* “diffraction suppressed MB”). They also included their underlying event data for $P_{T\text{max}} > 5$ GeV/c, but the errors on the data are large in this region and hence their UE data did not have much influence on the resulting tune. The ATLAS AMBT1 tune does significantly better at fitting the LHC “diffraction suppressed MB” data, but does not do so well at fitting the LHC underlying event data. I started with the ATLAS Tune AMBT1 and varied a few of the parameters to improve the fit to the CMS underlying event data at 900 GeV and 7 TeV. The parameters of the ATLAS Tune AMBT1 and the CMS UE Tune Z1 are shown in Table II.

TABLE II

PYTHIA 6.4 parameters for the ATLAS Tune AMBT1 and the CMS UE Tune Z1. Parameters not shown are set to their default value.

Parameter	Tune Z1	Tune Z2	AMBT1
PDF — Parton Distribution Function	CTEQ5L	CTEQ6L	LO*
PARP(82) — MPI Cut-off	1.932	1.832	2.292
PARP(89) — Reference energy, E_0	1800	1800	1800
PARP(90) — MPI Energy Extrapolation	0.275	0.275	0.25
PARP(77) — CR Suppression	1.016	1.016	1.016
PARP(78) — CR Strength	0.538	0.538	0.538
PARP(80) — Probability colored parton from BBR	0.1	0.1	0.1
PARP(83) — Matter fraction in core	0.356	0.356	0.356
PARP(84) — Core of matter overlap	0.651	0.651	0.651
PARP(62) — ISR Cut-off	1.025	1.025	1.025
PARP(93) — primordial kT-max	10.0	10.0	10.0
MSTP(81) — MPI, ISR, FSR, BBR model	21	21	21
MSTP(82) — Double gaussian matter distribution	4	4	4
MSTP(91) — Gaussian primordial kT	1	1	1
MSTP(95) — strategy for color reconnection	6	6	6

Tune Z1 is a PYTHIA 6.4 tune that uses the CTEQ5L PDF. CMS wanted also a PYTHIA 6.4 tune that uses the CTEQ6L PDF. I know from my experience with Tune DW and Tune D6 (Table I) that in going from CTEQ5L to CTEQ6L that I would have to decrease the value of $p_{T0} = \text{PARP}(82)$, so I decreased it by a factor of 0.95 (which is precisely the Tune D6 to Tune DW ratio) and produced Tune Z2. The parameters of Tune Z2 are also shown in Table II. In my haste I set $\epsilon = \text{PARP}(90) = 0.275$ for Tune Z2 which is the same value that I determined for Tune Z1.

Figure 14 shows the more recent CMS data at 900 GeV and 7 TeV [14] on the transverse charged particle density and the transverse charged PTsum density as defined by the leading charged particle jet, $\text{chgjet}\#1$. This data are corrected to the particle level and compared with PYTHIA Tune Z1 and Tune Z2. Tune Z1 does a much better job in describing the low p_T rise to the plateau than Tune DW. Tune Z2 does not describe the CMS UE data quite as well as Tune Z1.

Figure 15 shows CMS data on the ratio of 7 TeV and 900 GeV (7 TeV divided by 900 GeV) for the transverse charged particle density and the transverse charged PTsum density compared with PYTHIA Tune Z1, Tune Z2, and the PYTHIA 8 Tune 4C from Corke and Sjöstrand [15]. Tune Z1 and Tune Z2 have the same value of $\text{PARP}(90) = 0.275$, however, Tune Z1 fits the energy dependence quite nicely while Tune Z2 does not. In constructing

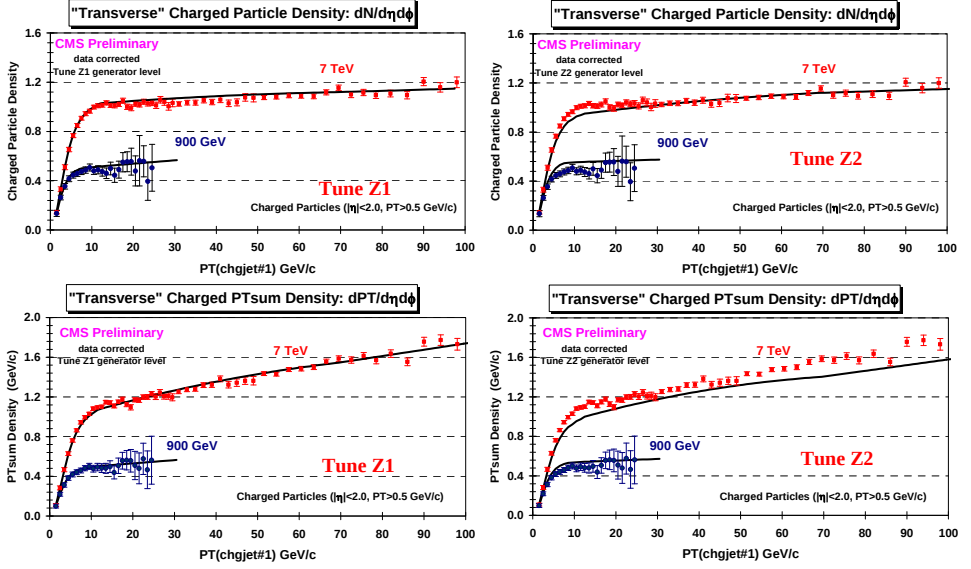


Fig. 14. (left column) CMS data at 900 GeV and 7 TeV [14] on the transverse charged particle density (top left) and the transverse charged PTsum density (bottom left) as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are corrected to the particle level and compared with PYTHIA Tune Z1 at the generator level. (right column) CMS preliminary data at 900 GeV and 7 TeV on the transverse charged particle density (top right) and the transverse charged PTsum density (bottom right) as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are corrected to the particle level and compared with PYTHIA Tune Z2 at the generator level.

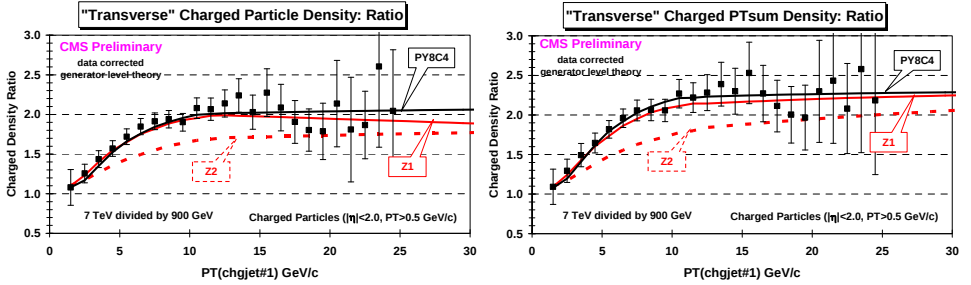


Fig. 15. CMS data on the ratio of 7 TeV and 900 GeV (7 TeV divided by 900 GeV from Fig. 14) for the transverse charged particle density (left) and the transverse charged PTsum density (right) as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are corrected to the particle level and compared and with PYTHIA Tune Z1, Tune Z2, and PYTHIA 8 Tune 4C [15] at the generator level.

Tune Z2, I forgot that the PDF also affects the energy dependence. When I changed from CTEQ5L (Tune Z1) to CTEQ6L (Tune Z2) I should have also changed $\epsilon = \text{PARP}(90)$ as well as $\text{PARP}(82)$. The PYTHIA 8 Tune 4C uses CTEQ6L but has $\epsilon = 0.19$ and fits the energy dependence very nicely. However, Tune 4C does not fit the LHC UE data at 900 GeV and 7 TeV as well as Tune Z1 does.

Figure 16 shows the latest ATLAS data [16] at 900 GeV and 7 TeV on the transverse charged particle density and the transverse charged PTsum density as defined by the leading charged particle, PTmax, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected to the particle level and compared with PYTHIA Tune Z1. Tune Z1 describes very well both the CMS and ATLAS UE data. Figure 17 compares the CMS data using chgjet#1 with the ATLAS data which uses PTmax approach. Tune Z1 describes the differences between the CMS chgjet#1 and the ATLAS PTmax approach very well. It is interesting that the activity in the “plateau” of the “transverse” region is larger for the chgjet#1 approach than it is for the PTmax analysis. Could it be that when one requires a charged particle jet with a certain value of $P_T(\text{chgjet}\#1)$ that you bias the UE to be more active, because a more active UE can contribute some p_T to the leading charged particle jet? In an attempt to understand this, in Fig. 17 I looked at the dependence of the transverse charged particle density on the charged particle jet size (*i.e.* radius) as predicted by PYTHIA Tune Z1. I constructed charged particle jets using the Anti-KT algorithm with $d = 0.2, 0.5$, and 1.0 . The charged particles have $p_T > 0.5$ GeV/c and $|\eta| < 2.5$ and for $d = 0.2, 0.5$, and 1.0 the leading charged particle jet is restricted to be in the region $|\eta(\text{chgjet}\#1)| < 1.5$. For very narrow jets the UE “plateau” is nearly the same as in the PTmax approach. As the jets

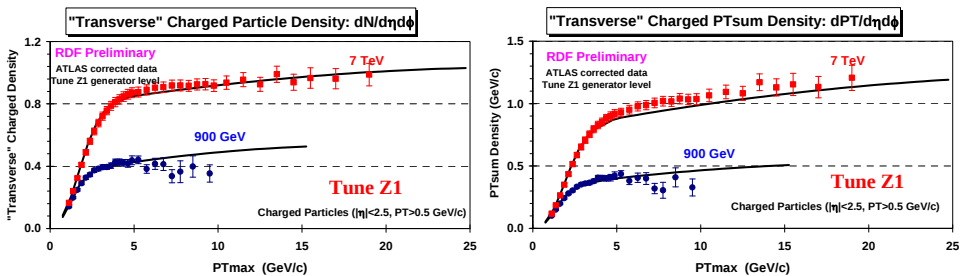


Fig. 16. ATLAS data at 900 GeV and 7 TeV [16] on the transverse charged particle density (left) and the transverse charged PTsum density (right) as defined by the leading charged particle, PTmax, as a function of PTmax for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected to the particle level and compared with PYTHIA Tune Z1 at the generator level.

become larger in radius the UE “plateau” becomes more active! The object that is being used to define the “transverse” region can bias the UE to be more active. Amazing!

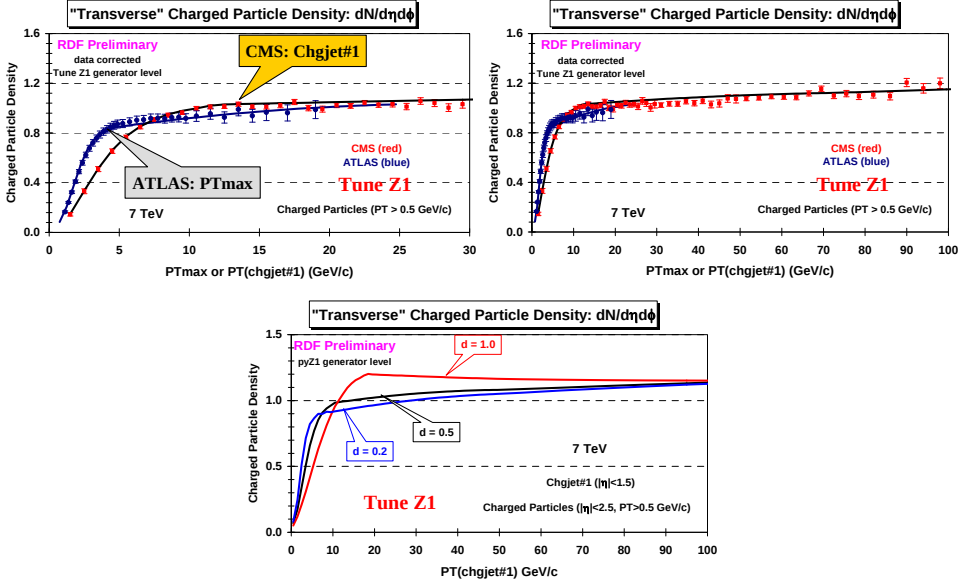


Fig. 17. CMS data from Fig. 14 on the charged particle density in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, versus $P_T(\text{chgjet}\#1)$ up to 100 GeV/c (top left) and up to 30 GeV/c (top right) compared with the ATLAS data from Fig. 16 on the charged particle density in the “transverse” region as defined by the leading charged particle, PT_{max} , versus PT_{max} . The data are corrected to the particle level and compared with PYTHIA Tune Z1 at the generator level. (bottom) Dependence of the transverse charged particle density on the charged particle jet radius as predicted by PYTHIA Tune Z1. Charged particle jets are constructed using the Anti-KT algorithm with $d = 0.2, 0.5$, and 1.0 . The charged particles have $p_T > 0.5$ GeV/c and $|\eta| < 2.5$ and the leading charged particle jet is restricted to be in the region $|\eta(\text{chgjet}\#1)| < 1.5$.

Figure 18 shows the recent ATLAS data at 7 TeV [16] on the transverse charged particle density and the transverse charged PT_{sum} density as defined by the leading charged particle, PT_{max} , for charged particles with $p_T > 0.1$ GeV/c and $|\eta| < 2.5$ compared with PYTHIA Tune Z1. Figure 18 also shows the ratio of the ATLAS data at with $p_T > 0.1$ GeV/c and $p_T > 0.5$ GeV/c compared with PYTHIA Tune Z1. All of the CDF UE measurements involved charged particles with $p_T > 0.5$ GeV/c. This is the first look at the UE in the region below 500 MeV/c and there are a lot of soft particles! The transverse charged particle density increases by about

a factor of 2 in going from $p_T > 0.5$ GeV/c to $p_T > 0.1$ GeV/c. Tune Z1 describes this increase better than Tune DW, however, Tune Z1 still does not have quite enough soft particles.

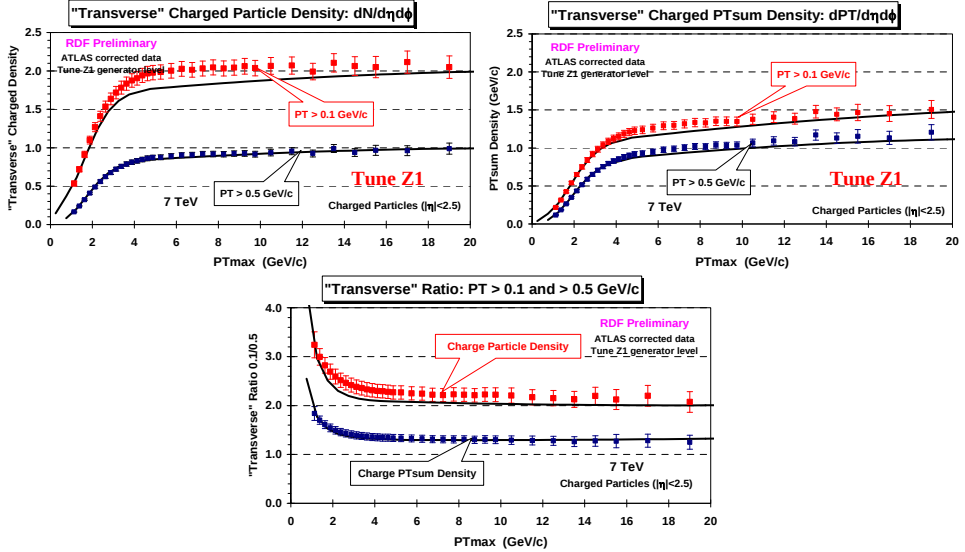


Fig. 18. ATLAS data at 7 TeV [16] on the transverse charged particle density (top left) and the transverse charged PTsum density (top right) as defined by the leading charged particle, PTmax, as a function of PTmax for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$ and for charged particles with $p_T > 0.1$ GeV/c and $|\eta| < 2.5$. The data are corrected to the particle level and compared with PYTHIA Tune Z1 at the generator level. (bottom) Ratio of the ATLAS data with $p_T > 0.1$ GeV/c and $p_T > 0.5$ GeV/c (100 MeV/c cut divided by 500 MeV/c cut) for the transverse charged particle density and the charged PTsum density as defined by the leading charged particle, PTmax, as a function of PTmax compared with PYTHIA Tune Z1.

Figure 19 shows the CDF data at 1.96 TeV on the charged particle density in the “transverse” region as defined by the leading calorimeter jet, jet#1, as a function of $P_T(\text{jet}\#1)$ together with the CMS data at 900 GeV and 7 TeV on the charged particle density in the “transverse” region as defined by the leading charged particle jet, chgjet#1, as a function of $P_T(\text{chgjet}\#1)$ compared with PYTHIA Tune Z1. Figure 19 shows the CMS PYTHIA 6.4 Tune Z1 and Fig. 13 shows the CDF PYTHIA 6.2 Tune DW. Neither of the tunes describe perfectly all three energies. Tune Z1 is in very good agreement with the UE data at 900 GeV and 7 TeV but is a little high at 1.96 TeV. One can see this in Fig. 20 which shows the PYTHIA Tune Z1 2-to-2 hard scattering cut-off, p_{T0} , at 900 GeV and 7 TeV as determined by fitting the CMS UE data in Fig. 14 together with the functional form of

PYTHIA, $p_{T0}(W_{\text{cm}}) = (W_{\text{cm}}/W_0)^\epsilon$, with $P_{T0} = \text{PARP}(82) = 1.932$ GeV, $\epsilon = \text{PARP}(90) = 0.275$, and $W_0 = 1.8$ TeV. Figure 20 also shows the value of p_{T0} at 1.96 TeV that would fit better the CDF data in Fig. 19. The PYTHIA functional form predicts a smaller cut-off at 1.96 TeV resulting in a more active UE than observed in the CDF “leading jet” data in Fig. 19 [17]. I believe it is premature to consider other functional forms for $P_{T0}(W_{\text{cm}})$. I believe that we will find a PYTHIA tune that simultaneously describes 900 GeV, 1.96 TeV, and 7 TeV. Remember the energy dependence of the UE depends not only on $\epsilon = \text{PARP}(90)$, but also on the choice of PDF!

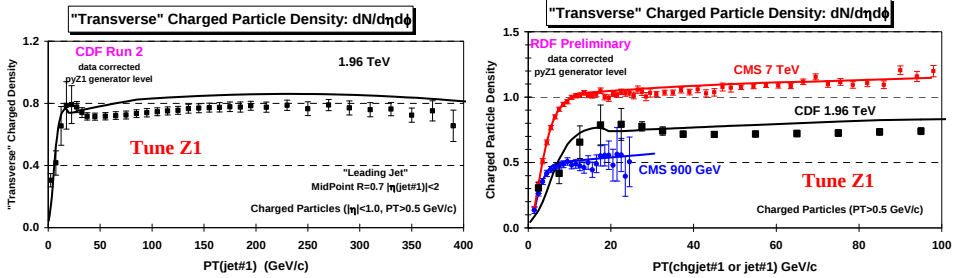


Fig. 19. (left) CDF data at 1.96 TeV from Ref. [13] on the charged particle density ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the “transverse” region as defined by the leading calorimeter jet, jet#1, as a function of $P_T(\text{jet}\#1)$ compared with PYTHIA Tune Z1. Also compares the CDF data at 1.96 TeV with the CMS data [14] at 900 GeV and 7 TeV (right) on the “transverse” charged particle density ($p_T > 0.5$ GeV/c, $|\eta| < 2$) in the “transverse” region as defined by the leading charged particle jet, chgjet#1, as a function of $P_T(\text{chgjet}\#1)$. The data are corrected to the particle level and compared with PYTHIA Tune Z1 at the generator level.

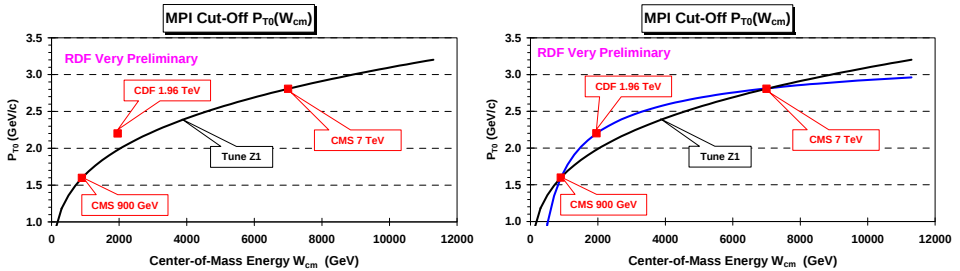


Fig. 20. (left) Shows the PYTHIA Tune Z1 2-to-2 hard scattering cut-off, p_{T0} , at 900 GeV and 7 TeV as determined by fitting the CMS UE data in Fig. 14 together with PYTHIA’s functional form of $p_{T0}(W_{\text{cm}}) = p_{T0}(W_{\text{cm}}/W_0)^\epsilon$ with $p_{T0} = \text{PARP}(82) = 1.932$ GeV/c, $\epsilon = \text{PARP}(90) = 0.275$ and $W_0 = 1.8$ TeV. Also, shows the value of p_{T0} at 1.96 TeV that would fit better the CDF data in Fig. 19. The PYTHIA functional form predicts a smaller cut-off at 1.96 TeV resulting in a more active UE than observed in the CDF leading jet data in Fig. 19. (right) Same as the left plot, but with an arbitrary functional form that extrapolates through the three energy points.

5. PYTHIA tunes and the LHC MB data

Since PYTHIA regulates both the primary hard scattering and the MPI with the same cut-off, p_{T0} , with PYTHIA one can model the overall “non-diffractive” (ND) cross-section by simply letting the transverse momentum of the primary hard scattering go to zero. The non-diffractive cross-section then consists of BBR plus “soft” MPI with one of the MPI occasionally being hard. In this naïve approach the UE in a hard-scattering process is related to MB collisions, but they are not the same. Of course, to model MB collisions one must also add a model of single (SD) and double diffraction (DD). This makes the modeling of MB much more complicated than the modeling of the UE. One cannot trust the PYTHIA 6.2 modeling of SD and DD.

Figure 21 shows the inelastic (INEL) data from ALICE and UA5 at 900 GeV [18] on the charged particle density, $dN/d\eta$ (all p_T) compared with PYTHIA Tune DW and Tune S320. Both these tunes are about 11% below the data. The INEL cross-section is the sum of ND + SD + DD. Figure 22 shows the non-single diffraction (NSD) data from CMS 7 TeV [19] on the charged particle density, $dN/d\eta$ (all p_T) compared with PYTHIA Tune DW. The solid curve is NSD and the dashed curve is inelastic non-diffraction (ND) component. The NSD cross-section is the sum of ND + DD. Figure 22 also shows the INEL data from ALICE at 900 GeV [20] on the charged particle density, $dN/d\eta$, with $p_T > p_{Tcut}$ and with at least one charged particle with $p_T > p_{Tcut}$ and $|\eta| < 0.8$ for $p_{Tcut} = 0.15$ GeV/ c , 0.5 GeV/ c , and 1.0 GeV/ c compared with PYTHIA Tune DW. Tune DW was tuned to fit the Tevatron data with $p_T > 0.5$ GeV/ c . Two things change when we extrapolate from the Tevatron to the LHC. Of course the center-of-mass energy changes, but also we have started looking at softer particles (*i.e.* $p_T < 500$ MeV/ c). Figure 22 shows that Tune DW works well for $p_T > 0.5$ GeV/ c , but does not

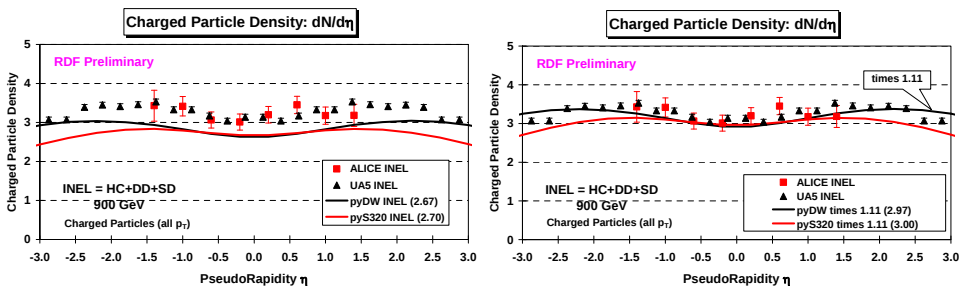


Fig. 21. (left) The inelastic (INEL) data from ALICE and UA5 at 900 GeV [18] on the charged particle density, $dN/d\eta$ (all p_T) compared with PYTHIA Tune DW and Tune S320. (right) Same as the left plot except the Monte Carlo model predictions have been multiplied by a factor of 1.11.

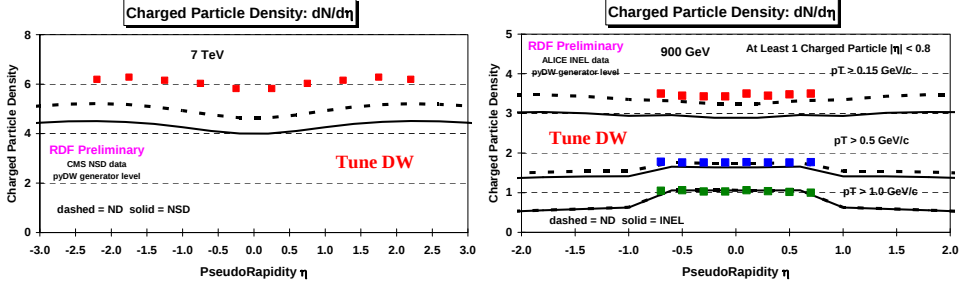


Fig. 22. (left) The non-single diffraction (NSD) data from CMS at 7 TeV [19] on the charged particle density, $dN/d\eta$ (all p_T) compared with PYTHIA Tune DW. The solid curve is NSD and the dashed curve is inelastic non-diffraction (ND) component. (right) The inelastic (INEL) data from ALICE at 900 GeV on the charged particle density, $dN/d\eta$, with $p_T > \text{PTcut}$ and at least one charged particle with $p_T > \text{PTcut}$ and $|\eta| < 0.8$ for $\text{PTcut} = 0.15 \text{ GeV}/c$, $0.5 \text{ GeV}/c$, and $1.0 \text{ GeV}/c$ compared with PYTHIA Tune DW. The solid curve is the INEL and the dashed curve is inelastic non-diffraction (ND) component.

produce enough soft particles below $500 \text{ MeV}/c$. One can also see that, at least in PYTHIA 6.2, the modeling of SD and DD is more important at the lower p_T values.

Figure 23 compares the CMS and ALICE charged particle densities, $dN/d\eta$, with PYTHIA 6.4 Tune Z1. Tune Z1 does a better job at fitting the MB data than does Tune DW and it produced more soft particles below $500 \text{ MeV}/c$ than does Tune DW. However, Tune Z1 does not fit the MB data perfectly.

Figure 24 compares the activity in the UE of a hard scattering process with an average MB collision. The activity in the UE of a hard scattering process at 7 TeV is roughly a factor of two greater than it is for an average MB collision and Tune Z1 describes this difference fairly well. In PYTHIA this difference comes from the fact that there are more MPI in a hard scattering process than in a typical MB collision. By demanding a hard scattering you force the collision to be more central (*i.e.* smaller impact parameter), which increases the chance of MPI.

Figure 25 shows the data from CMS at 900 GeV and 7 TeV [21] on the charged particle multiplicity distribution ($|\eta| < 2$, all p_T) compared with PYTHIA Tune Z1 and the data from CMS at 900 GeV and 7 TeV on the charged particle multiplicity distribution in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, for $P_T(\text{chgjet}\#1) > 3.0 \text{ GeV}/c$ compared with PYTHIA Tune Z1. You are asking a lot of the QCD Monte Carlo model when you expect it to simultaneously describe both MB and the UE in a hard scattering process. I think it is amazing that Tune Z1 does as well as it does in describing both!

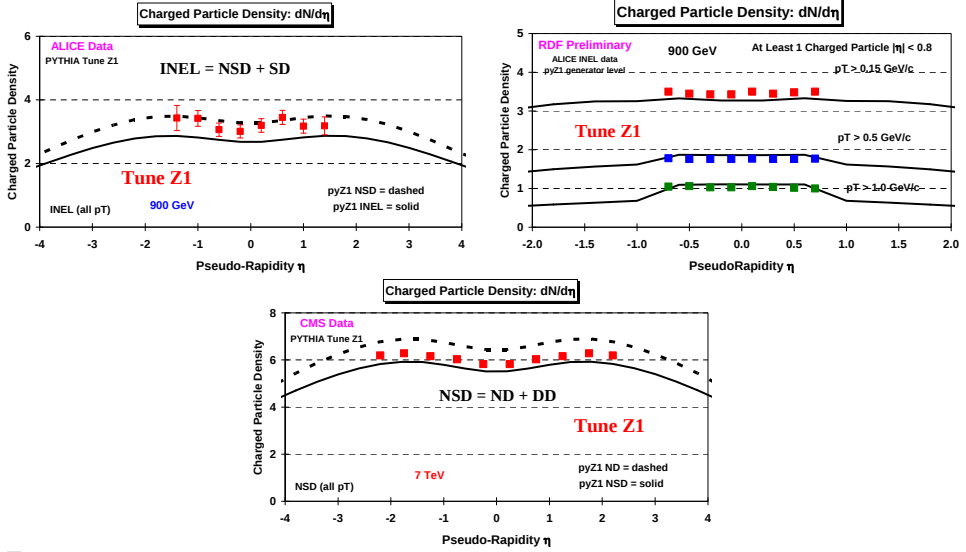


Fig. 23. (top left) The inelastic (INEL) data from ALICE at 900 GeV [18] on the charged particle density, $dN/d\eta$ (all p_T) compared with PYTHIA Tune Z1. The solid curve is the INEL and the dashed curve is non-single diffraction (NSD) component. (top right) The inelastic (INEL) data from ALICE at 900 GeV on the charged particle density, $dN/d\eta$, with $p_T > PT_{cut}$ and at least one charged particle with $p_T > PT_{cut}$ and $|\eta| < 0.8$ for $PT_{cut} = 0.15$ GeV/c, 0.5 GeV/c, and 1.0 GeV/c compared with PYTHIA Tune Z1. (bottom) The non-single diffraction (NSD) data from CMS 7 TeV on the charged particle density, $dN/d\eta$ (all p_T) compared with PYTHIA Tune Z1. The solid curve is NSD and the dashed curve is inelastic non-diffraction (ND) component.

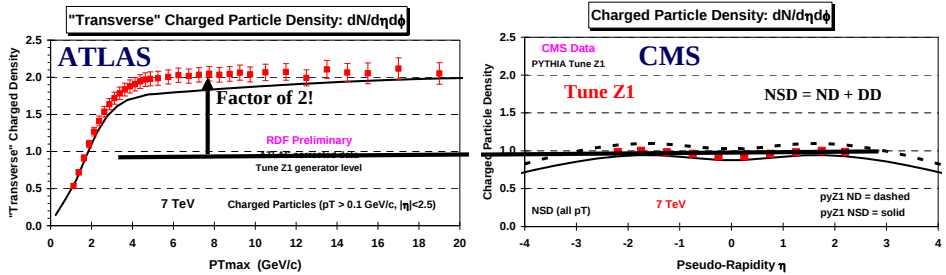


Fig. 24. (right) The non-single diffraction (NSD) data from CMS 7 TeV [19] on the charged particle density, $dN/d\eta d\phi$ (all p_T) compared with PYTHIA Tune Z1. The data and theory on $dN/d\eta$ in Fig. 23 has been divided by 2π to construct the number of particles per unit $\eta-\phi$. (left) ATLAS data from Fig. 18 at 7 TeV on the charged particle density in the “transverse” region as defined by the leading charged particle, PT_{max} , as a function of PT_{max} for charged particles with $p_T > 0.1$ GeV/c and $|\eta| < 2.5$ compared with PYTHIA Tune Z1. The activity in the UE of a hard scattering process (left) is a factor of two greater than in an average MB collision (right).

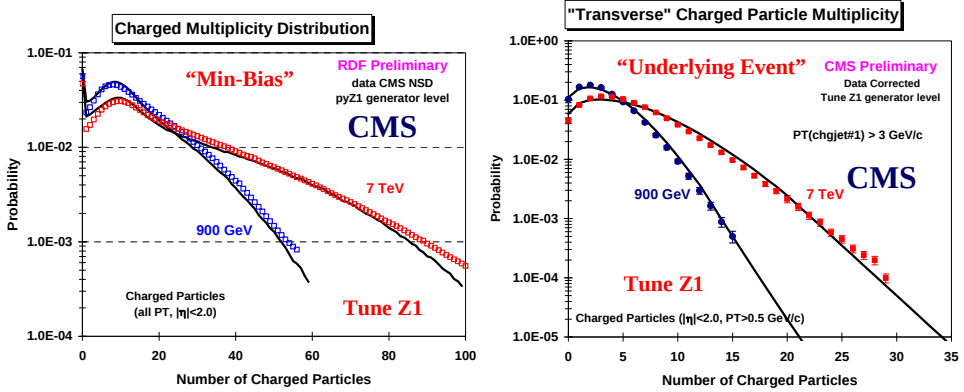


Fig. 25. (left) The non-single diffraction (NSD) data from CMS at 900 GeV and 7 TeV [21] on the charged particle multiplicity distribution ($|\eta| < 2$, all p_T) compared with PYTHIA Tune Z1. (right) Data from CMS at 900 GeV and 7 TeV [14] on the charged particle multiplicity distribution ($|\eta| < 2$, $p_T > 0.5$ GeV/c) in the “transverse” region as defined by the leading charged particle jet, $\text{chgjet}\#1$, for $P_T(\text{chgjet}\#1) > 3.0$ GeV/c compared with PYTHIA Tune Z1. The data have been corrected to the particle level and compared with Tune Z1 at the generator level.

6. Summary and conclusions

The PYTHIA 6.2 Tune DW which was created from CDF UE studies at the Tevatron did a fairly good job in predicting the LHC UE data 900 GeV and 7 TeV. The behavior of the UE at the LHC is roughly what we expected. Remember this is “soft” QCD! The LHC PYTHIA 6.4 Tune Z1 does a very nice job describing the UE data at 900 GeV and 7 TeV. The UE is part of a hard scattering process. MB collisions quite often contain no hard scattering and are therefore more difficult to model. Since PYTHIA regulates both the primary hard scattering and the MPI with the same cut-off, p_{T0} , with PYTHIA one can model the overall non-diffractive (ND) cross-section by simply letting the transverse momentum of the primary hard scattering go to zero. In this naïve approach the UE in a hard-scattering process is related to MB collisions, but they are not the same. Of course, to model MB collisions one must also add a model of single (SD) and double diffraction (DD). Tune Z1 does a fairly good job of simultaneously describing both MB and the UE in a hard scattering process. I think it is amazing that it does as well on MB as it does.

There are a lot of factors of two floating around. The charged particle density in the “transverse” region increases by about a factor of two in going from 900 GeV and 7 TeV (Fig. 15). At 7 TeV the charged particle density in the “transverse” region increases by about a factor of two in going from

$p_T > 500 \text{ MeV}/c$ to $p_T > 100 \text{ MeV}/c$ (Fig. 18). The charged particle density in the “transverse” region is about a factor of two larger than the density of particles in a typical MB collision (Fig. 24). All of these factors of two are described fairly well by PYTHIA Tune Z1. PYTHIA 8 [22] also does a fairly good job on many of the MB observables, but so far it does not fit the LHC UE data as well as Tune Z1.

In order to describe the bulk of the LHC MB data, one must include a model of diffraction. Experimentally, it is not possible to uniquely separate diffractive from non-diffractive collisions. However, one can construct samples of “diffraction enhanced MB” and “diffraction suppressed MB” events and compare with the models. The “diffraction enhanced MB” samples are selected by requiring some type of rapidity gap [23, 24]. We have learned that PYTHIA 6 does a poor job of modeling of diffraction. PHOJET [25] and PYTHIA 8 do a better job with diffraction.

In a very short time the experiments at the LHC have collected a large amount of data that can be used to study MB collisions and the UE in great detail. This data can be compared with the Tevatron MB and UE data to further constrain and improve the QCD Monte Carlo models we use to simulate hadron–hadron collision. At present none of the tunes describe perfectly the UE data at both the Tevatron and the LHC. However, I believe the tunes will continue to improve. We are just getting started! The future will include more comparisons with PYTHIA 8, HERWIG++ [26], and SHERPA [27].

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