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The Energy Dependence of the Underlying Event in Hadronic Collisions

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At CDF we study charged particle production (p_T > 0.5 GeV/c, $|\eta|$ < 0.8) in proton-antiproton collisions at 300 GeV, 900 GeV, and 1.96 TeV. The 300 GeV and 900 GeV data are a result of the "Tevatron Energy Scan" which was performed just before the Tevatron was shut down. We use the direction of the leading charged particle in each event, PTmax, to define three regions of η-ϕ space; "toward", "away", and "transverse". The "transverse" region is further divided into the "transMAX" and "transMIN" contributions. The "transMIN" region is very sensitive to the multiple parton interaction component (MPI) of the "underlying event", while the "transDIF" ("transMAX" minus "transMIN") is very sensitive to the initial and final-state radiation. This CDF analysis together with LHC data provides a detailed study the energy dependence of the various components of the "underlying event" in hadronic collisions.

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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. The CDF MB trigger requires at least one charged particle in the forward region $3.2 < \eta < 5.9$ and simultaneously at least one charged particle in the backward region $-5.9 < \eta < -3.2$, where the pseudo-rapidity $\eta = -\log(\tan(\theta_{cm}/2))$. The underlying event (UE) consists of 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. To study the UE we use MB data, however, 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 structure of the hard hadron-hadron collision to experimentally study the UE. As illustrated in Figure 1, on an event-by-event bases, a "leading object" is used to define regions of η-ϕ space, where η is the pseudo-rapidity and θ_{cm} is the center-of-mass polar scattering angle [1,2]. Here we use the highest transverse momentum charged particle in the event, PTmax, as the leading object. On an event by event basis, we define "transMAX" ("transMIN") to be the maximum (minimum) number of charged particles or the *scalar* p_T sum of charged particles in the two "transverse" regions, $60^o < \Delta\phi < 120^o$, $|\eta| < \eta_{cut}$ and $60^o < -\Delta\phi < 120^o$, $|\eta| < \eta_{cut}$. Densities are then formed by dividing by the area in η-ϕ space. "TransMAX" and "transMIN" each have an area of $\Delta\eta\Delta\phi = 2\eta_{cut}\times2\pi/6$, where we take $\eta_{cut} = 0.8$. The overall "transverse" region (*i.e.* "transAVE") is the average of the "transMAX" and the "transMIN" regions.

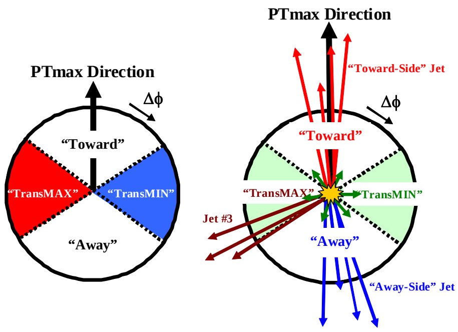

Figure 1. (*left*) Illustration of correlations in azimuthal angle $\Delta\phi$ relative to the direction of the leading charged particle in the event, PTmax. The relative angle $\Delta\phi = \phi - \phi_{MAX}$, where ϕ_{MAX} is the azimuthal angle of PTmax and ϕ is the azimuthal angle of a charged particle. On an event by event basis, we define "transMAX" ("transMIN") to be the maximum (minimum) of the two "transverse" regions, $60^o < \Delta\phi < 120^o$, $|\eta| < \eta_{cut}$ and $60^o < -\Delta\phi < 120^o$, $|\eta| < \eta_{cut}$, where we take $\eta_{cut} = 0.8$. The overall "transverse" region (*i.e.* "transAVE") is the average of the "transMAX" and the "transMIN" regions. (*right*) llustration of the topology of a hadron-hadron collision in which a "hard" parton-parton collision has occurred. The "toward" region contains the leading "jet", while the "away" region, on the average, contains the "away-side" "jet". For events with large initial or final-state radiation the "transMAX" region contains the third jet, while both the "transMAX" and "transMIN" regions receive contributions from the MPI and beam-beam remnants. Thus, the "transMIN" region is very sensitive to the MPI and beam-beam remnants, while the "transMAX" minus the "transMIN" (*i.e.* "transDIF") is very sensitive to initial and final-state radiation.

Figure 1 illustrates the topology of a hadron-hadron collision in which a "hard" parton-parton collision has occurred. The "toward" region contains the leading "jet", while the "away" region, on the average, contains the "away-side" "jet". For events with large initial or final-state radiation the "transMAX" region contains the third jet, while both the "transMAX" and "transMIN" regions receive contributions from the MPI and beam-beam remnants. Thus, the "transMIN" region is very sensitive to the MPI and beam-beam remnants, while "transDIF" ("transMAX" minus the "transMIN") is very sensitive to initial and final-state radiation [3].

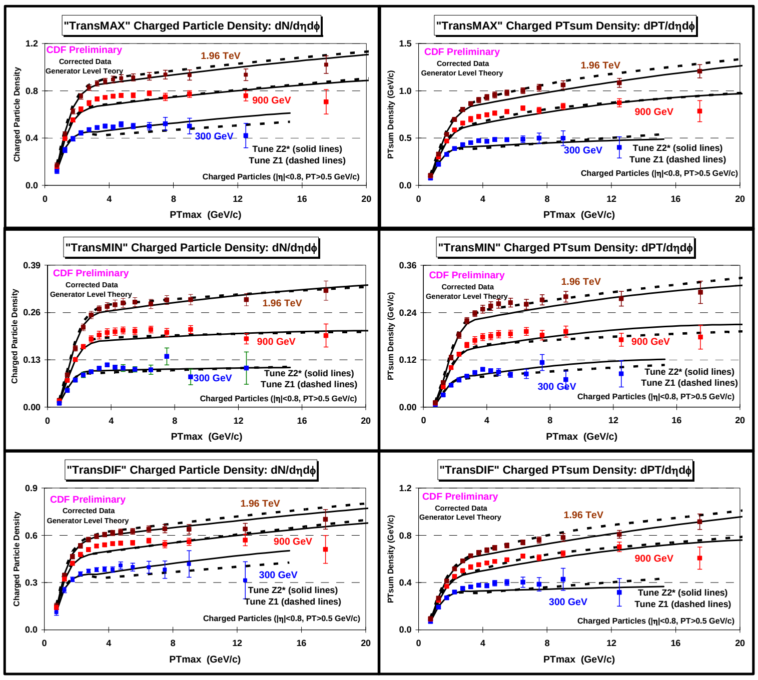

Figure 2. Preliminary CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the "transMAX" charged particle density (*top left*), the "transMAX" charged PTsum density (*top right*), the "transMIN" charged particle density (*middle left*), the "transMIN" charged PTsum density (*middle right*), the "transDIF" charged particle density (*bottom left*), and the "transDIF" charged PTsum density (*bottom right*) as defined by the leading charged particle, PTmax, as a function of PTmax. The "transDIF" density is equal to the "transMAX" density minus the "transMIN" density. The charged particles have $p_T > 0.5$ GeV and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty and are compared with PYTHIA 6.4 Tune Z1 and Tune Z2* at the generator level.

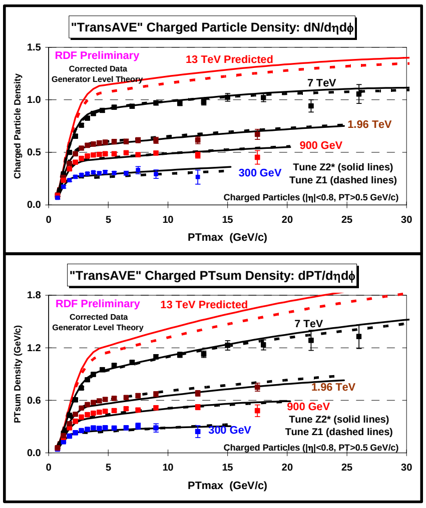

Figure 3. Preliminary CMS data [9] at 7 TeV and preliminary CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the "transAVE" charged particle density (*top*) and the "transAVE" charged PTsum density (*bottom*) as defined by the leading charged particle, PTmax, as a function of PTmax. The "transAVE" density is equal to the average of the "transMAX" density and the "transMIN" density (*i.e.* overall "transverse" density). The charged particles have $p_T >$ 0.5 GeV and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty and are compared with PYTHIA 6.4 Tune Z1 and Tune Z2* at the generator level. The predictions at 13 TeV are also shown.

Figure 2 shows the preliminary CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the "transMAX", "transMIN", and "transDIF" charged particle and PTsum densities as defined by the leading charged particle, PTmax, as a function of PTmax. The charged particles have $p_T >$

0.5 GeV and |η| < 0.8. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty and are compared with PYTHIA 6.4 Tune Z1 and Tune Z2* at the generator level. QCD Monte-Carlo generators such as PYTHIA [4] 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" [5,6]. Tune Z1 (CTEQ5L) and Tune Z2* (CTEQ6L) are PYTHIA 6.4 tunes that were constructed by fitting CMS UE data at 900 GeV and 7 TeV [7,8]. Both tunes do a fairly good (although not perfect) job in describing the CDF UE data at 1.96 TeV, 900 GeV, and 300 GeV.

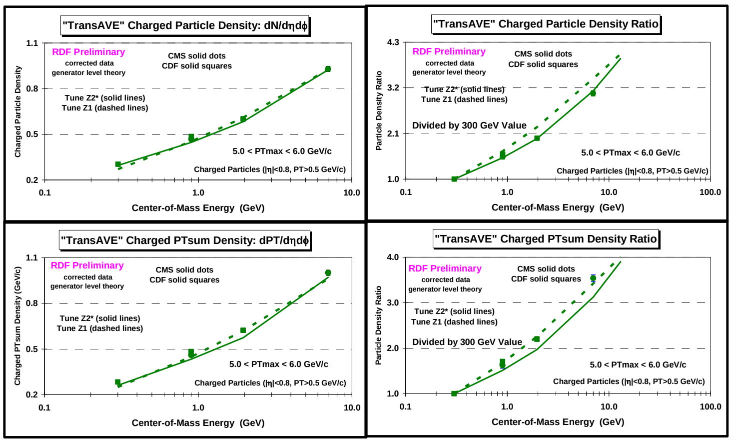

Figure 4. (*left column*) Preliminary CMS data [9] at 7 TeV and 900 GeV (solid squares) and preliminary CDF data at 1.96 TeV, 900 GeV, and 300 GeV (solid dots) on the "transAVE" charged particle density (*top*) and the "transAVE" charged PTsum density (*bottom*) as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c versus the center-of-mass energy (*log scale*). The "transAVE" density is equal to the average of the "transMAX" density and the "transMIN" density (*i.e.* overall "transverse" density). (*right column*) Ratio of the data to the corresponding value at 300 GeV for the "transAVE" charged particle density (*top*) and the "transAVE" charged PTsum density (*bottom*) as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c versus the center-of-mass energy (*log scale*). The charged particles have p_T > 0.5 GeV and |η| < 0.8. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty and are compared with PYTHIA 6.4 Tune Z1 and Tune Z2* at the generator level extrapolated to 13 TeV (*right column*).

Figure 3 shows preliminary CMS data [9] at 7 TeV together with preliminary CDF data at 1.96 TeV, 900 GeV, and 300 GeV for the "transAVE" charged particle and PTsum densities as defined by the leading charged particle, PTmax, as a function of PTmax. The "transAVE" density is equal to the average of the "transMAX" density and the "transMIN" density (*i.e.* overall "transverse" density). Figure 4 shows preliminary CMS data [9] at 7 TeV and 900 GeV together with CDF data at 1.96 TeV, 900 GeV, and 300 GeV for the "transAVE" charged particle and PTsum densities as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c versus the center-of-mass energy. Figure 4 also shows the ratio of the data to the corresponding value at 300 GeV for the "transAVE" charged particle and PTsum densities. The "transAVE" charge particle density increases by a factor of about 3.0 in going from 300 GeV to 7 TeV, while the PTsum density increase by a factor of about 3.5. This is a reflection of the fact that the "transverse" average p_T of the charged particles is increasing. Both Tune Z1 and Tune Z2* do a fairly good (although not perfect) job in describing the energy dependence of "transAVE".

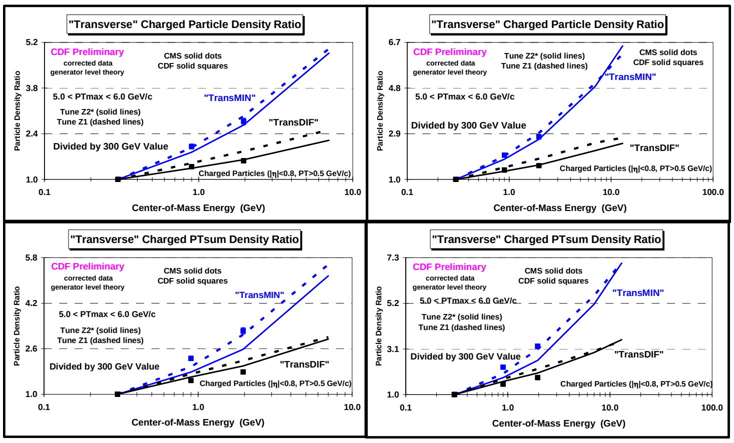

Figure 5. Preliminary CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the "transMIN" and "transDIF" charged particle density (*top row*) and the "transMIN" and "transDIF" charged PTsum density (*bottom row*) as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c versus the center-of-mass energy (*log scale*). The plots show the ratio of the data to the corresponding value at 300 GeV. The charged particles have p_T > 0.5 GeV and $|\eta|$ < 0.8. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty and are compared with PYTHIA 6.4 Tune Z1 and Tune Z2* at the generator level extrapolated to 7 TeV (*left column*) and 13 TeV (*right column*).

Figure 5 shows the energy dependence of the "transMIN" and "transDIF" components. The "transMIN" density (more sensitive to MPI & BBR) increases much faster with center-of-mass energy than does the "transDIF" density (more sensitive to ISR & FSR). The MPI increases like a power of the center-of-mass energy, while the ISR & FSR increase logarithmically. Tune Z2* predicts that the "transMIN" charged particle density increases by factor of around 6.6 in going from 300 GeV to 13 TeV, while the "transDIF" charged particle density is predicted to increase by only a factor of around 2.5. This is the first time we have seen the different energy dependences of these two components. Previously we only had information on the energy dependence of the "transAVE" charge particle density. Both Tune Z1 and Tune Z2* do a fairly good (although not perfect) job in describing the energy dependence of "transMIN" and "transDIF". What we are learning will allow for a deeper understanding of the BBR and MPI which will result in more precise predictions at the future LHC energies of 13 and 14 TeV.

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