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Study of Soft QCD at the Tevatron CDF note 9789

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Summary. — Measurements of particle production and inclusive differential cross sections in inelastic pp collisions are reported together with studies of the underlying event in various event topologies. A comparison with MonteCarlo model predictions at the hadron level is performed. The aim is to provide data that can be used to improve QCD models of minimum-bias production and of the underlying event.

PACS `13.85.Hd` – Inelastic scattering: many-particle final states .
PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles .

1. – Introduction

At the energy of the Tevatron Collider "soft" non-perturbative hadron interactions represent the largest part of the inelastic cross section. A minimum-bias (MB) trigger is usually employed to collect samples of soft collisions, but such a trigger is actually meant to collect events from all possible inelastic interactions proportionally to their natural production rate. Therefore MB physics offers a chance for studying both the theoretically poorly understood softer phenomena and the interplay between the soft and the hard (perturbative) interactions [1].

The observables that are experimentally accessible in the MB final state represent a complicated mixture of different physics effects. The available MonteCarlo models may be tuned to give an acceptable description of single observables, but are unable to describe simultaneously the entire set. In order to simulate accurately a minimum-bias sample, it is necessary not only a model of the "ordinary" QCD 2-to-2 parton scattering process both in the perturbative (hard) and in the non-perturbative (soft) regime; also the knowledge of the correct mixture of soft and hard collisions and a reliable description of all softer components of the interaction are necessary [3]. Such softer components may be recognized as the ramains of the hard scattering not associated with the hard process ("beam-beam remnants", BBR) and as other 2-to-2 parton-parton scatterings other than the hard one ("multiple parton interactions", MPI) ([1]). Is is customary to define the sum of BBR + MPI final state particles as "underlying event". The understanding of the underlying event is expecially important for precision measurements of many high-p_T observables where it forms an unavoidable background (see, *e.g.* [4]). This is especially true in high luminosity environments such as at the Large Hadron Collider [5].

Here three distinct but correlated and complementary studies will be described. The first addresses the features of inelastic inclusive particle production, the second addresses the description of the "underlying event", and the third investigates speficically the modeling of MPI.

2. – MB Studies

This analysis [2] is based on an integrated luminosity of 506 pb^{-1} collected with the CDF II detector [6] at $\sqrt{s} = 1.96$ TeV during the first Tevatron stores in Run II. Two systems of gas Cherenkov counters (CLC) [7], covering the pseudorapidity forward regions $3.7 < |\eta| < 4.7$, are used to determine the luminosity. The MB trigger is implemented by requiring a coincidence in time of signals in both forward and backward CLC modules. The sample collected consists of inelastic central interactions with a small contamination of diffractive events. The average instantaneous luminosity is about $20 \times 10^{30} cm^{-2}s^{-1}$.

All data presented is corrected for the trigger and vertex efficiency, undetected pile-up and event selection acceptance. The background of diffractive interactions is subtracted. Primary charged particles are measured in the region of $|\eta| < 1$ and $p_T > 0.4$ GeV/c, and are corrected for the tracking efficiency, contamination of secondary particles and mis-identified tracks.

A set of simulated Monte Carlo (MC) events about twice the size of the data sample was generated with PYTHIA [8] "Tune A" [9]. To model the mixture of hard and soft interactions, PYTHIA introduces a p_T^0 cut off parameter that regulates the divergence of the 2-to-2 parton-parton perturbative cross section at low momenta. This parameter is used also to regulate the additional parton-parton scatterings that may occur in the same collision [10]. Thus, fixing the amount of multiple-parton interactions (*i.e.* setting the p_T cut-off) allows the hard 2-to-2 parton-parton scattering to be extended all the way down to $p_T(hard) = 0$ without hitting a divergence. The amount of hard scattering in simulated MB events is, therefore, related to the activity of the so-called underlying event in the hard scattering processes. The final state, likewise, is subject to several effects such as the treatments of the beam remnants and color (re)connection effects.

2·1. *Single Particle p_T Spectrum.* – The differential single particle invariant p_T differential cross section $d^3\sigma/p_T\Delta\phi\Delta y dp_T$ is shown in fig. 1. This measurement was last published by the CDF ([11]) for 1800 GeV data. The new measurement extends the p_T spectrum from 10 to over 100 GeV/c and is about 4% higher in cross-section. The tail of the distribution is at least three orders of magnitude higher than what could be expected by extrapolating to high p_T the function that fits the 1800 GeV data. In order to fit the whole spectrum, we introduced a more complex parametrization (eq.1):

$$f = A \left(\frac{p_0}{p_T + p_0} \right)^n + B \left(\frac{1}{p_T} \right)^s . \tag{1}$$

([1]) secondary parton-parton collisions may also have large momentum transfer but at the Tevatron energy such rare events may be neglected in the MB sample

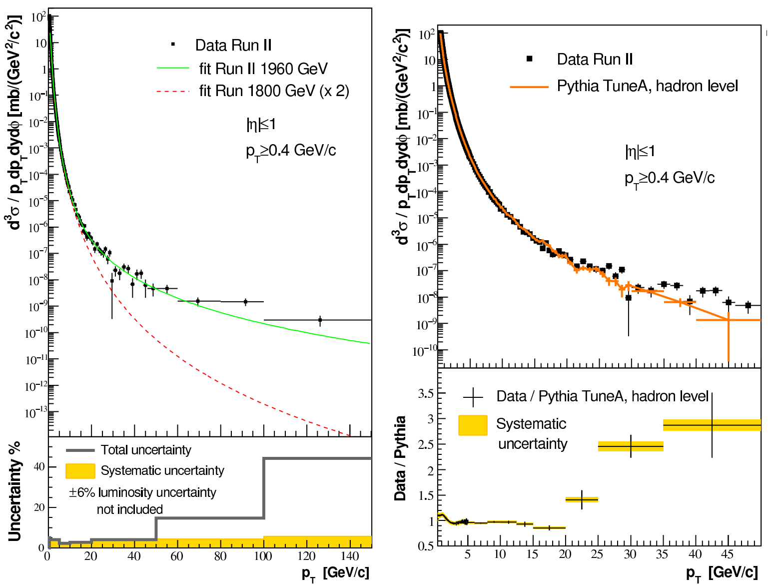

Fig. 1. – *Left:* the track p_T differential cross section with statistical uncertainty is shown. All particle tracks are assumed to be pions. A fit to the functional form used in the 1800 GeV analysys is also shown (dashed line). The fit with the more complex function (eq.1) is shown as a continuous line. In the plot at the bottom, the systematic and the total uncertainties are shown. *Right:* comparison with PYTHIA Tune A simulation at hadron level. The ratio of data over prediction is shown in the lower plot. Note that these distributions are cut off at 50 GeV/c since PYTHIA does not produce particles at all beyond that value.

Fig. 1 (right) shows a comparison with PYTHIA simulation at hadron level. The data show a larger cross section than simulation at high p_T starting from about 20 GeV/c. The MC generator does not produce any particles at all beyond 50 GeV/c.

2·2. *Event* $\sum E_T$ *Cross Section.* – The differential cross section $d^3\sigma/(\Delta\phi\Delta\eta d\sum(E_T))$ for $|\eta| < 1$ is shown in fig. 2. The event average transverse energy sum is $\sum E_T = 10.4 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.})$ GeV. This kind of measurement is new to the field, and represents a first attempt at describing the full final state including neutral particles. In this regard, it is complementary to the charged particle measurement in describing the global features of the inelastic $p\bar{p}$ cross section. The PYTHIA simulation does not closely reproduce the data over the whole $\sum E_T$ spectrum. In particular the peak of the MC distribution is slightly shifted to higher energies with respect to the data.

3. – UE Studies

It is possible to take advantage of the topological structure of hadron collisions to study the underlying event. The goal is a systematic study of final-state observables that may be used to tune and improve QCD MonteCarlo models of the underlying event. Three event topologies have been used. In the "leading jet" events a single jet is required in $|\eta| < 2$ [12]. The particles arising from BBR and MPI may hardly be experimentally

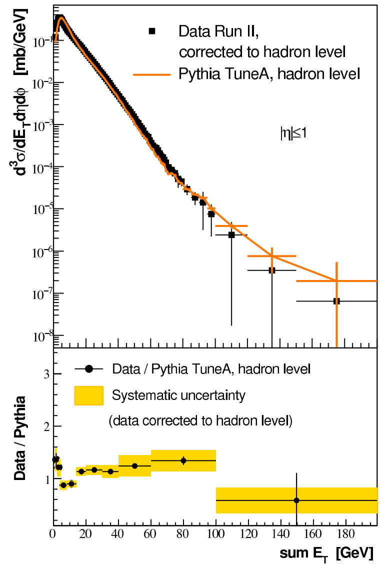

Fig. 2. – The differential $\sum E_T$ cross section in $|\eta| < 1$ compared to a PYTHIA prediction at hadron level. The ratio of data to PYTHIA Tune A is shown in the lower plot.

separated from those originated by the initial and final state gluon radiation (ISR, FSR). Drell-Yan lepton pair production is a unique event topology for UE studies since there is no final-state gluon radiation [13].

The result data presented here are collected by the CDF II experiment. Charged particles are measured in $|\eta| < 1$ and $p_T > 0.5$ GeV/c and are corrected to particle level. Tracking efficiency and effects of pile-up are corrected for. Jet data are based on a sample of about 2.2 fb^{-1} collected with various jet triggers. Jets are reconstructed using the MidPoint cone based algorithm with cone size of 0.7 and $f_{merge} = 0.75$. They are required to lie in $|\eta| < 2$ and the measure of their transverse energy E_T is corrected for the calorimeter response and acceptance [14]. Drell-Yan data are based on a sample of about 2.7 fb^{-1} collected with a lepton (electron or muon) trigger. These events are selectd by requiring two leptons of opposite charge ($e^{\pm}$ or $\mu^{\pm}$) with $p_T > 20$ GeV/c, $|\eta| < 1$, and invariant mass of the pair in the range $70 < |M_{pair}| < 110$ GeV with $|\eta_{pair}| < 6$. They are often referred to as "Z-boson" events.

In all cases, the direction of the leading jet (or of the Z-boson) is used to define four regions in $\eta - \phi$ space. The "toward" region is defined to be in $|\Delta\phi| < 60^o$ where

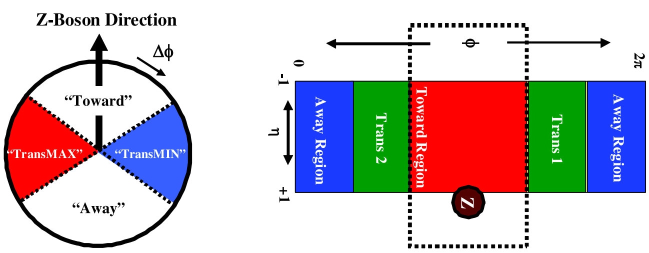

Fig. 3. – The "away", "toward" and "transverse" regions in ϕ (left) and η (right).

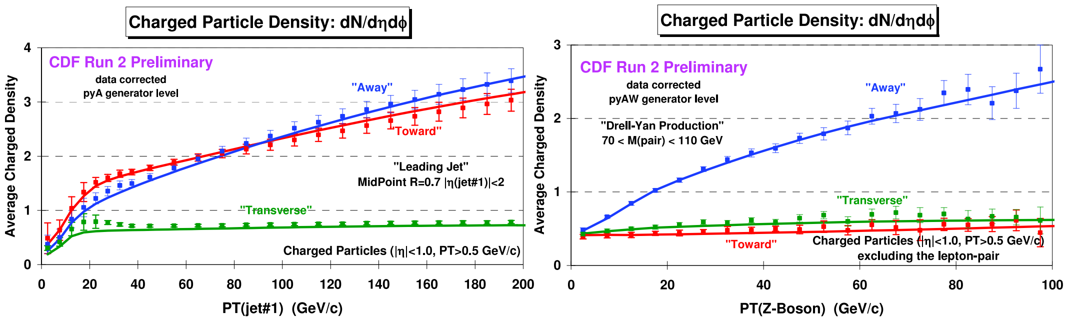

Fig. 4. – The "away", "toward" and "transverse" regions for leading-jet (left) and Drell-Yan (right) events.

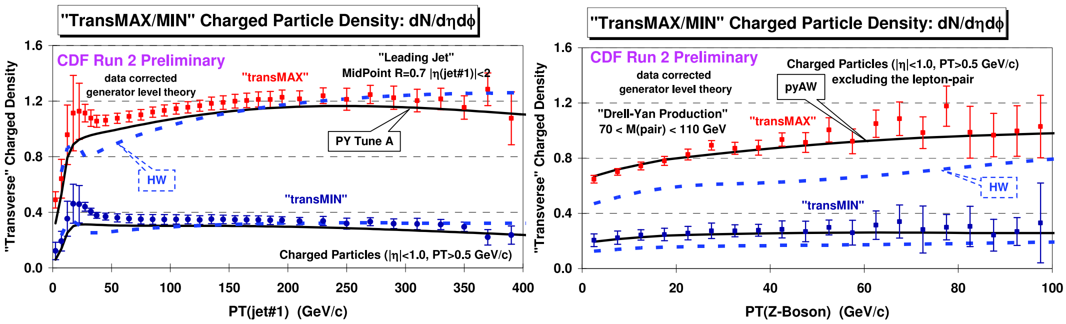

Fig. 5. – The "transMAX" and "transMIN" regions for leading-jet (left) and Drell-Yan (right) events. A comparison with PYTHIA TuneA (AW) and HERWIG is shown.

$\Delta\phi = \phi - \phi_{jet}$ is the relative azimuthal angle between a charged particle and the direction of the leading jet (or Z-boson); the "away" region in $|\Delta\phi| > 120$; the regions in $60^o < \Delta\phi < 120^o$ and $60^o < -\Delta\phi < 120^o$ are called "transverse".

In high-p_T jet production the "forward" and "away" regions receive large energy and particle contributions from the jets, while the "transverse" regions, orthogonal to the plane of the hard 2-to-2 scattering, are more sensitive to the UE. A "MAX" and "MIN" transverse region are defined to be, respectively, the one containing the largest (smallest) number of charged particles or scalar p_T sum of particles. It is expected that "transMAX" will pick up the hardest ISR/FSR contribution, while the contribution from the UE will be the same for both. Therefore the "transMIN" will be more sensitive to the UE. In Drell-Yan production the forward region, after excluding the two leptons, is very similar to the "transMIN" region that is less likely to receive contributions from ISR. With low p_T Z-bosons, essentially everything other than the final lepton pair is the underlying event. Large p_T bosons generate additional gluons via bremsstrahlung, resulting in multi-parton final states fragmenting into hadrons and forming away-side jets, but in the "toward" and "transverse" regions only the underlying event remains (fig.4).

Since the regions observed have different $\eta - \phi$ areas, some observables are built as densities of number of charged particles ($dN/d\eta d\phi$) or of scalar p_T sum of particles ($dp_T/d\eta d\phi$) by dividing by the area. Also other observables are studied, like the average

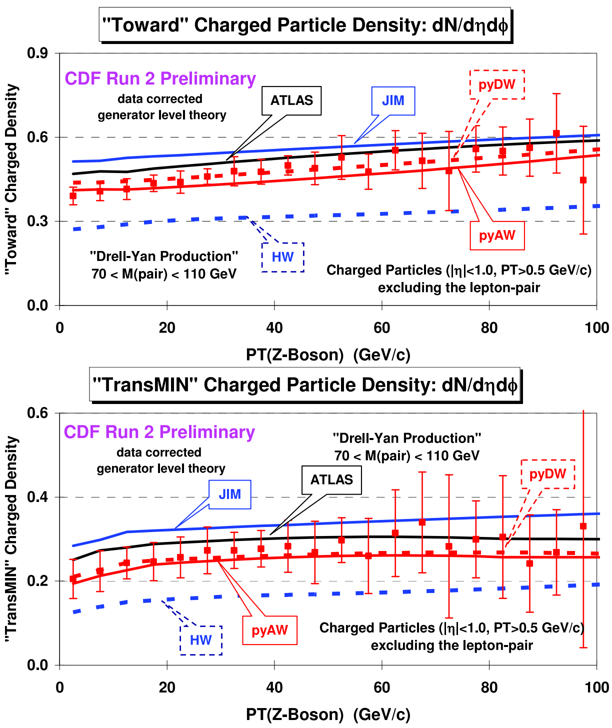

Fig. 6. – The "toward" and "transMIN" regions charged particle densities in Drell-Yan events compared to PYTHIA and HERWIG.

($\langle p_T \rangle$) and the maximum p_T of charged particles. All are analyzed as a function of the p_T of the leading jet or of the Z-boson.

Many observables have been studied in all event topologies and compared to a variety of MC models. Only few can be shown here, but it is important that MC generators be tuned on a wide range of observables and topologies. PYTHIA TuneA is compared to the leading-jet sample and TuneAW to the Drell-Yan sample. The two tunes differ only in that TuneAW fits also the Z-boson p_T distribution [15] as well as the underlying event. Other PYTHIA tunes, for example the one used by the ATLAS Collaboration, have also been considered. Details of these tunes may be found in [5] and references therein. The HERWIG MonteCarlo generator [16] does not provide any multiple parton-parton interaction mechanism, but an ad hoc MPI generator called JIMMY [17] may be added to improve the agreement with the underlying event observables. Details on the relative tunes may be found in [13].

From fig.5 it is clear that HERWIG, without MPI, does not produce enough activity in the transverse regions for either process. Disagreement is stronger in Drell-Yan than in leading-jet event because the lack of MPI becomes more evident in absence of FSR. The $\langle p_T \rangle$ plots (not shown here) show that in HERWIG the charged particle p_T distributions for both processes are also too soft.

In fig.6 the "toward" and "transMIN" regions are compared. The particle densities are larger in the former than in the latter, a feature which is well described by PYTHIA but not by HERWIG that produces too few particles. When adding MPI (JIMMY) the particle density becomes too large. All MC models considered fit well the sum p_T density $dp_T/d\eta d\phi$ in these regions.

4. – Dependence of $\langle p_T \rangle$ with N_{ch}

The rate of change of the average charged particle momentum $\langle p_T \rangle$ *versus* the charged particle multiplicity N_{ch} is one of the variables most sensitive to the combination of the various physical effects present in MB collisions, and is also the most poorly reproduced by the available MC generators [1]. It may be seen as a measure of the amount of hard *versus* soft processes, but it is also sensitive to the modeling of the multiple-parton interactions (MPI) [18]. If only two processes contribute to the MB final state, one soft, and one hard (the hard 2-to-2 parton-parton scattering), then demanding large N_{ch} would preferentially select the hard process and lead to a high $\langle p_T \rangle$. However, we see from fig. 7 (TuneA *no MPI*) that with these two processes alone, the average p_T increases much too rapidly. MPI provide 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. By introducing this mechanism, PYTHIA in the Tune A configuration gives a fairly good description of the correlation.

PYTHIA TuneAW also reproduces fairly well the same correlation in Drell-Yan events, while HERWIG (not shown here) rises too sharply due to the lack of MPI.

It is interesting to compare the MB data to a softer Drell-Yan subsample selected for

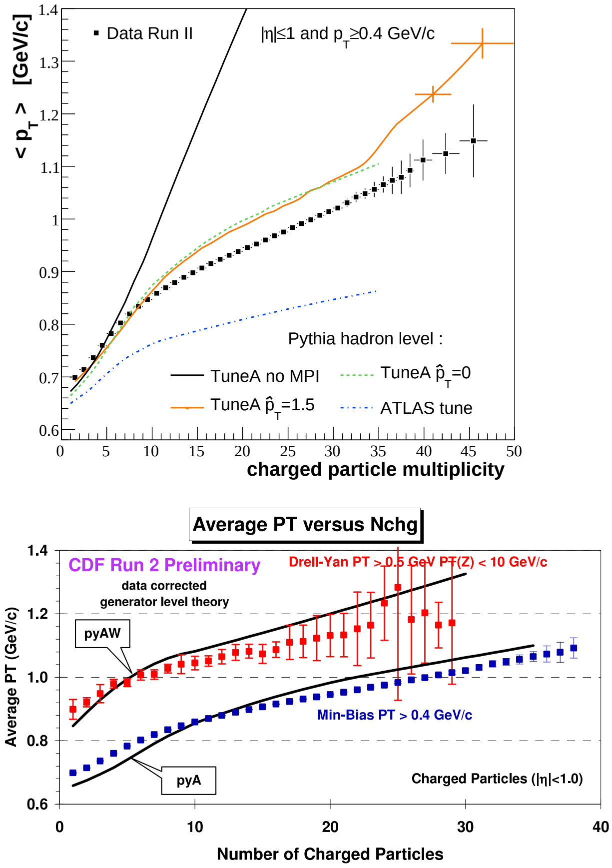

Fig. 7. – *Upper:* the dependence of the average charged particle p_T on the event multiplicity is shown for the MB sample. A comparison with various PYTHIA tunes at hadron level is shown. Tune A with $\hat{p}_{T0} = 0$ GeV/c is very similar to $\hat{p}_{T0} = 1.5$ GeV/c. The same tuning with no multiple parton interactions allowed ("no MPI") yields an average p_T much higher than data for multiplicities greater than about 5. The ATLAS tune yields too low an average p_T over the whole multiplicity range. The uncertainties shown are only statistical.
Lower: the average charged particle p_T *versus* the multiplicity of charged particles in MB and Drell-Yan events compared to PYTHIA TuneA and TuneAW.

having a p_T of the Z-boson < 10 GeV/c. This selection suppresses the high-p_T away side jet so that the higher particle multiplicities may be originated by MPI and ISR only. There is no a priori reason for the two samples to agree. However, they are remarkably similar and described fairly well by PYTHIA TuneA and TuneAW, respectively. This suggests that MPI are playing a similar role in both these processes.

5. – Conclusions

A set of precision measurements of the MB and UE was provided and compared to the available MC models. The MB sample shows no sign of discontinuity in the transition from soft to hard interactions. All data analysed favor models with multiple parton-parton interactions. Pythia may be tuned to reproduce the MB inclusive distributions and the features underlying event both in jet and Drell-Yan samples.

The behavior of the average charged particle p_T *versus* the charged particle multiplicity turns out to be an important observable sensible to the mixing of soft and hard processes and to the modeling of MPI. No available model correctly reproduces this correlation among particles in the final state. The distribution is found to be remarkably similar in MB and in low-p_T Drell-Yan events.

The results presented will lead to a better understanding of soft hadron interactions and to more precise high-p_T measurements at the Tevatron and at the Large Hadron Collider.

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