Minimum Bias Studies at CDF and Comparison with MonteCarlo

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Abstract
Measurements of particle production and inclusive differential cross sections in inelastic $p\bar{p}$ collisions are reported. The data were collected with a minimum-bias trigger at the Tevatron Collider with the CDF II experiment. Previous measurements are widely extended in range and precision. A comparison with a PYTHIA prediction at the hadron level is performed. Inclusive particle production is fairly well reproduced only in the low transverse momentum range. Final state correlation measurements are poorly reproduced, but favor models with multiple parton interactions.

1 Introduction

In hadron collisions, hard interactions are theoretically well described as collisions of two incoming partons along with softer interactions from the remaining partons. The so-called minimum-bias (MB) interactions, on the contrary, can only be defined through a description of the experimental apparatus that triggers the collection of the data. Such a trigger is meant to collect events from all possible inelastic interactions proportionally to their natural production rate. MB physics offers a unique ground for studying both the theoretically poorly understood softer phenomena and the interplay between the soft and the hard perturbative interactions.

The understanding of the softer components of MB is interesting not only in its own right, but is also important for precision measurements of hard interactions in which soft effects need to be subtracted (see, e.g. [**?**]). The observables that are experimentally accessible in the MB final state represent a complicated mixture of different physics effects such that most models could readily be tuned to give an acceptable description of each single observable, but not to describe simultaneously the entire set. Effects due to multiple parton parton interactions (MPI) are essential for an exhaustive description of inelastic non-diffractive hadron interactions.

2 The CDF Detector and Data Samples

2.1 The Data Collection and Event Selection

This analysis is based on an integrated luminosity of 506 pb^{1} collected with the CDF II detector at $\sqrt{s} = 1.96$ TeV during the first Tevatron stores in Run II. CDF II is a general purpose detector that combines precision charged particle tracking with projective geometry calorimeter towers. A detailed description of the detector, with detailed information about the transverse momentum (p_T) and transverse energy (E_T) resolutions, can be found elsewhere [**?**].

Two systems of gas Cherenkov counters (CLC) [**?**], 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.

Only runs with lower initial instantaneous luminosity have been used in order to reduce the effects of event pile-up. The average instantaneous luminosity of the full MB sample is roughly 20×10^{30} cm^{-2}s^{-1}. For measurements where the calorimeter is involved, only a subsample of average luminosity 17×10^{30} cm^{-2}s^{-1} was used.

Primary vertices are identified by the convergence of reconstructed tracks along the $z-$axis. For vertices reconsructed from less than ten tracks a requirement that they be symmetric is added: the quantity $|(N^+N)/(N^+ + N)|$, where $N^\pm$ is the number of tracks in the positive or negative η hemisphere, cannot equal one. Only events that contain one, and only one, primary vertex in the fiducial region $|Z_{vtx}| \leq 40$ cm centered around the nominal CDF $z = 0$ position are accepted. This fiducial interval is further restricted to $|Z_{vtx}| \leq 20$ cm when measurements with the calorimeter are involved.

2.2 The MonteCarlo Sample

A sample of simulated Monte Carlo (MC) events about twice the size of the data was generated with PYTHIA version 6.2 [**?**], with parameters optimized for the best reproduction of minimum-bias interactions. To model the mixture of hard and soft interactions, PYTHIA Tune A [**?**] [**?**] 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 [**?**]. 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. The pythia Tune A results presented here are the predictions, not fits.

A run-dependent simulation with a realistic distribution of multiple interactions was employed to compute corrections and acceptance. Events were fully simulated through the detector and successively reconstructed with the standard CDF reconstruction chain. All data is corrected to hadron level. The definition of primary particles was to consider all particles with mean lifetime $\tau > 0.3 \times 10^{-10}$ s produced promptly in the $p\bar{p}$ interaction, and the decay products of those with shorter mean lifetimes. With this definition strange hadrons are included among the primary particles, and those that are not reconstructed are corrected for. On the other hand, their decay products (mainly $\pi^\pm$ from K_S^0 decays) are excluded, while those from heavier flavor hadrons are included.

3 Results

3.1 Efficiency and Acceptance Corrections

Reconstructed tracks are accepted if they comply with a minimal set of quality selections. Primary charged particles are selected by requiring that they originate in a fiducial region around the $p\bar{p}$ vertex. In order to optimize the efficiency and acceptance conditions particles are required to have a transverse momentum greater than 0.4 GeV/c and pseudorapidity $|\eta| \leq 1$.

The transverse energy sum ($\sum E_T$) is computed in the limited region $|\eta| \leq 1$ as the scalar sum over the calorimeter towers of the transverse energies in the electromagnetic and hadronic compartments. The calorimeter response has been evaluated with MC. The region below about 5 GeV is the most critical. The reliability of MC in evaluating the calorimeter response was checked against the single particle response measured from data. The simulation of the energy deposition of neutral particles was assumed to be correct.

In the end, all data presented is corrected for the trigger and vertex efficiency, undetected pile-up, diffractive background and event selection acceptance. Charged particle measurements are corrected also for the tracking efficiency, contamination of secondary particles (particle interaction, pair creation), particle decays and mis-identified tracks. These quantties are evaluated as a function of p_T, in different ranges of track multiplicity. The total correction includes also the smearing correction for very high p_T tracks, where the small curvature may cause a significant dispersion in the measure of the momentum. $\sum E_T$ measurements are corrected for the calorimeter response and acceptance, and are unfolded to correct the dispersion due to the finite calorimeter resolution.

3.2 The charged particle p_T spectrum

We may write the single-particle invariant p_T differential cross section as:

$$E\frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{p_T \Delta\phi \Delta y dp_T} = \frac{N_{pcles}/(\varepsilon \times A)}{\mathcal{L} p_T \Delta\phi \Delta y dp_T} , \tag{1}$$

where E, p, ϕ, and y are the particle energy, momentum, azimuthal angle and rapidity, respectively; N_{pcles} is the raw number of charged particles that is to be corrected for all efficiencies (ε) and acceptance (A). $\mathcal{L}$ is the effective time-integrated luminosity of the sample. The accepted region in Δy is calculated from the η for each charged track, always assuming the charged pion mass. The differential cross section is shown in Fig. 1.

This measure was discussed in [**?**] and last published by the CDF collaboration in 1988 [**?**]. There is a scale factor of 2 between the 1988 and the new measurement, due to different normalization. Besides this, the new measurement is about 4% higher than the previous one. At least part of this difference may be explained by the increased center-of-mass energy of the collisions from 1800 to 1960 GeV. The new measurement extends the momentum spectrum from 10 to over 100 GeV/c, and enables verification of the empirical modeling of minimum-bias production up to the high p_T production region.

We observe that modeling the spectrum with the power-law form used in 1988 to fit the distribution, does not account for the high p_T tail observed in this measurement (Fig. 1, left). Nevertheless, in the limited region up to $p_T = 10$ GeV/c, we obtain, for the present data, a set of fit parameters compatible with those published in 1988. In our measurement, 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 low p_T region. In order to fit the whole spectrum, we introduced a more complex parametrization by adding a second term to the function used in [?] (Eq.2):

$$f = A\left(\frac{p_0}{p_T + p_0}\right)^n + B\left(\frac{1}{p_T}\right)^s . \tag{2}$$

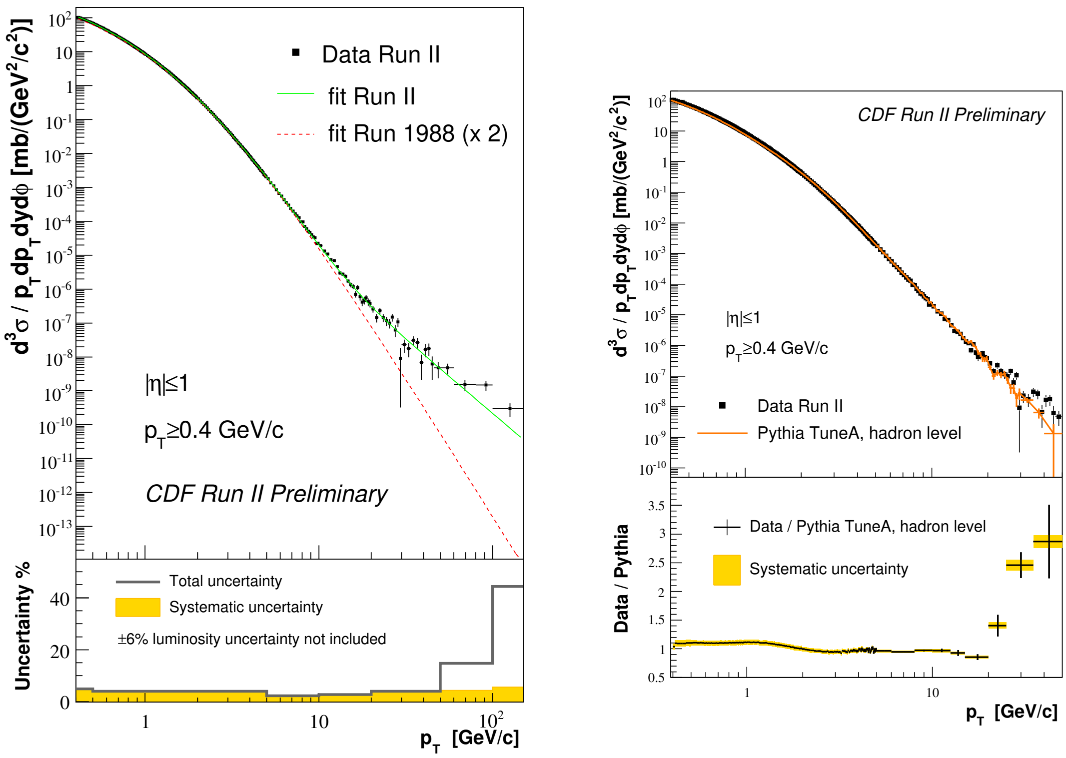

Fig. 1: *Left:* the track p_T differential cross section with statistical uncertainty is shown. A fit to the functional form used in the 1988 analysys in the region of $0.4 < p_T < 10$ GeV/c is also shown (dashed line). The fit with the more complex function (Eq.2) is shown as a continuous line. In the 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.

With this empirical function, we obtain a good χ^2 but the data are still not well reproduced above about 100 Gev/c.

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

3.3 The dependence of $\langle p_T \rangle$ on the particle multiplicity

The dependence of the particle transverse momentum on multiplicity ($\langle p_T \rangle(N_{ch})$) is computed as the average p_T of all charged primary particles in events with the same charged multiplicity (N_{ch}), as a function of N_{ch}. A study of $\langle p_T \rangle(N_{ch})$ was already performed by CDF in Run I and published in [**?**]. This new measurement benefits from the larger statistics obtained with a dedicated "high multiplicity" trigger. Data from this trigger are included by merging them into the MB sample.

This is one of the variables most sensitive to the combination of the various physical effects present in MB collisions, and is also the variable most poorly reproduced by the available MC generators. The rate of change of $\langle p_T \rangle$ versus N_{ch} is a measure of the amount of hard versus soft processes contributing to minimum-bias collisions; in simulation the rate is sensitive to the modeling of the multiple-parton interactions (MPI) [?].

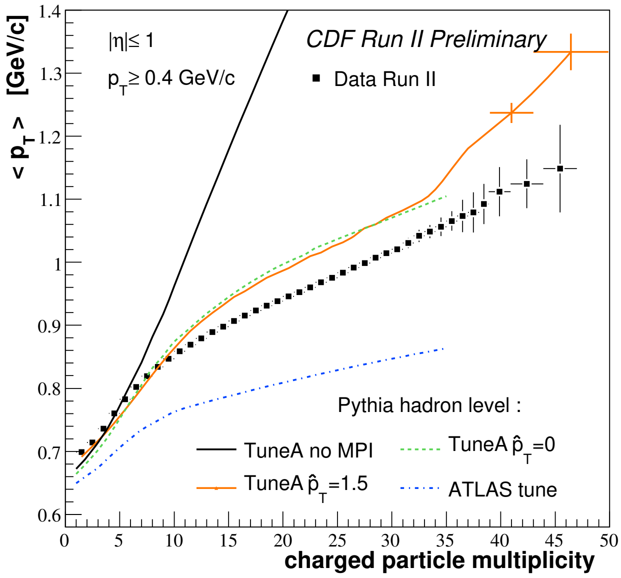

Fig. 2: The dependence of the average charged particle p_T on the event multiplicity is shown. A comparison with various PYTHIA tunes at hadron level is shown. Tune A with $\hat{p}_{T0} = 1.5$ GeV/c was used to compute the MC corrections in this analysis (the statistical uncertainty is shown only for the highest multiplicities where it is significant). 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.

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. 2 (Tune A, 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 $\langle p_T \rangle (N_{ch})$ and, although the data are quantitatively not exactly reproduced, there is great progress over fits to Run I data [?]. The systematic uncertainty is always within 2%, a value significantly smaller than the discrepancy with data.

3.4 The $\sum E_T$ spectrum

The differential cross section $d^3\sigma/(\Delta\phi\Delta\eta dE_T)$ for $|\eta| < 1$ is shown in Fig. 3. The raw and corrected event average transverse energies are $E_T = 7.350 \pm 0.001(\text{stat.})$ and $E_T = 10.4 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.})$ GeV, respectively.

The measurement of the event transverse energy sum 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.

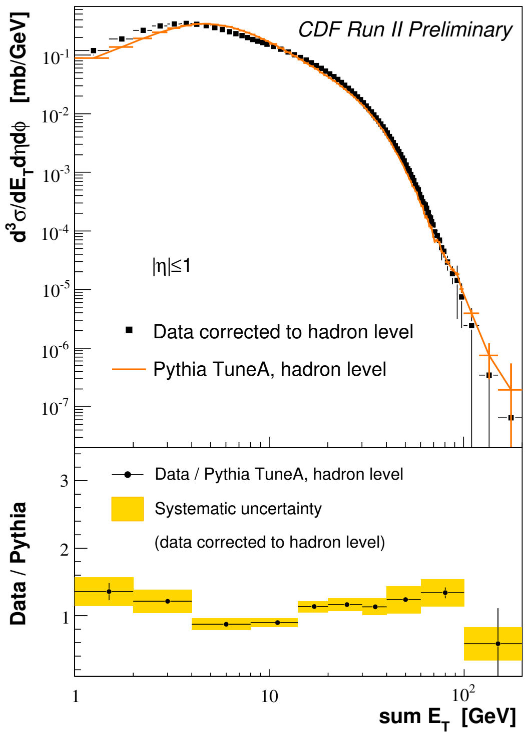

Fig. 3: The differential $\sum E_T$ cross section in $|\eta| < 1$ compared to a PYTHIA prediction at hadron level. The ratio of data to PYTHIA Tune A is shown in the lower plot.

3.5 Systematic Uncertainties

We have detected several possible sources of systematic uncertainties. The largest ones are the uncertainties on the calorimeter response (up to 15% at lower $\sum E_T$), on the pile-up correction, on the diffractive background, and the uncertainty related to the MC generator used to compute the various corrections. These uncertainties are, in general, larger in the $\sum E_T$ measurement than in charged particle measurements.

There is an overall global 6% systematic uncertainty on the effective time-integrated luminosity measurement [**?**] that is to be added to all the cross section measurements.

4 Experimentl Hot Topics

4.1 The MB trigger

The acceptance of the MB trigger has been measured by comparing it to a sample of zero-bias events collected during the same period. The zero-bias data set is collected without any trigger requirements, simply by starting the data acquisition at the Tevatron radio-frequency signal. The results indicate that the acceptance depends on a number of variables, most of which are, in some way, related to the number of tracks present in the detector: number of interactions, number of tracks, instantaneous luminosity and the CLC calibration. We parametrized the dependence on these variables so that a correction could be applied on an event-by-event basis. The total trigger acceptance therefore increases linearly with the instantaneous luminosity. As a function of the reconstructed number of tracks, the acceptance is well represented by a typical turn-on curve starting at about 20% (few tracks) and reaching its plateau with a value between 97 and 99% for about 15 tracks.

4.2 Pile Up

In spite of the low instantaneous luminosity, the selected data sample contains a contamination of pile-up events. This is due to multiple interactions when the separation between $p\bar{p}$ collisions is less than the vertex resolution in the $z-$coordinate (about 3 cm).

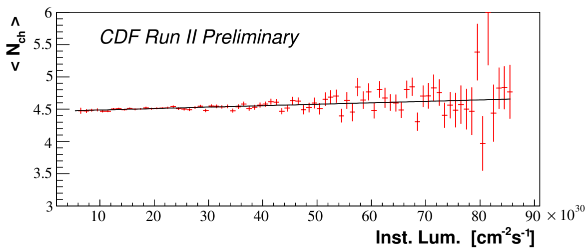

Fig. 4: The raw event average charged particle multiplicity as a function of the instantaneous luminosity. The line represents a linear fit (with slope equal to 0.0022±0.0003). The uncertainty is statistical only.

The number of undetected events was estimated indirectly by plotting the average N_{ch} as a function of the instantaneous luminosity (Fig. 4). In this plot, the increase in $\langle N_{ch} \rangle$ is due to the increase in number of pile-up events. We assume that virtually no pile-up is present at a luminosity of $\mathcal{L} = 1 \times 10^{30}$ cm^{-2}s^{-1}. The difference with respect to the $\langle N_{ch} \rangle$ at the average luminosity of the sample yields the estimated number of events that went unobserved.

However, although the pile-up probability in the low luminosity sample is small ($< 1\%$), it is not negligible. By assuming conservatively an uncertainty on the MB inelastic-non-diffractive cross section used by the MC generator of 6 mb, we calculate that this is equivalent to a variation in the sample average luminosity of 2.5×10^{30} cm$^{-2}s^{-1}$. This, in turn, corresponds to an uncertainty $< 3\%$ on the $\sum E_T$ distribution and negligible on the charged particle distributions.

5 Conclusions

A set of high precision measurements of the final state in minimum-bias interactions is provided and compared to the best available MC model.

The former power-law modeling of the single particle p_T spectrum is not compatible with the high momentum tail ($p_T \geq 10$ GeV/c) observed in data. The more recent tunings of the PYTHIA MC generator (Tune A) reproduce the inclusive charged particle p_T distribution in data within 10% up to $p_T \simeq 20$ GeV/c but the prediction lies below the data at high p_T.

The $\sum E_T$ cross section represents the first attempt to measure the neutral particle activity in MB. PYTHIA Tune A does not closely reproduce the shape of the distribution.

The mechanism of multiple parton interactions (with strong final-state correlations among them) has been shown to be very useful in order to reproduce high multiplicity final states with the correct particle transverse momenta. In fact, the data very much disfavor models without MPI, and put strong constraints on multiple-parton interaction models.

The data presented here can be used to improve QCD Monte Carlo models and further our understanding of multiple parton interactions. A detailed understanding of MB interactions is especially important in very high luminosity environments (such as at the LHC) where a large number of such interactions is expected in the same bunch crossing.

References