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First Measurement of the Underlying Event Activity at the LHC with $\sqrt{s} = 0.9$ TeV

The CMS Collaboration*

Abstract

A measurement of the underlying activity in scattering processes with p_T scale in the GeV region is performed in proton-proton collisions at $\sqrt{s} = 0.9$ TeV, using data collected by the CMS experiment at the LHC. Charged hadron production is studied with reference to the direction of a leading object, either a charged particle or a set of charged particles forming a jet. Predictions of several QCD-inspired models as implemented in PYTHIA are compared, after full detector simulation, to the data. The models generally predict too little production of charged hadrons with pseudorapidity $|\eta| < 2$, $p_T > 0.5\,\mathrm{GeV}/c$, and azimuthal direction transverse to that of the leading object.

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1 Introduction

In the presence of a “hard” process characterized by large transverse momenta p_T with respect to the beam direction, the hadronic final states of hadron-hadron interactions can be described as the superposition of several contributions: products of the partonic hard scattering with the highest p_T, including initial and final state radiation; hadrons produced in additional “multiple parton interactions” (MPI); and “beam-beam remnants” (BBR) resulting from the hadronization of the partonic constituents that did not participate in other scatters. Products of MPI and BBR form the “underlying event” (UE). The UE cannot be uniquely separated from initial and final state radiation.

A good description of UE properties is crucial for precision measurements of Standard Model processes and the search for new physics at the CERN Large Hadron Collider (LHC) [1]. Multiplicity distributions measured by the UA5 collaboration at the Sp$\bar{\text{p}}$S collider [2] were modeled in Monte Carlo (MC) simulations [3]. Detailed UE studies performed at the Tevatron by the CDF collaboration [4–6] led to significant progress in MPI modeling [7]. The UE dynamics is, however, not fully understood, especially the centre-of-mass energy dependence. A new energy domain is opening with the LHC, where UE properties can be studied with data taken at $\sqrt{s} = 0.9, 7$, and 14 TeV. The data at 0.9 TeV analyzed in this paper provide a valuable reference point to progress in the understanding of UE and MPI.

UE properties are conveniently analyzed with reference to the direction of the particle or of the jet with largest p_T. This “leading” object is expected to reflect the direction of the parton produced with the highest transverse momentum in the hard interaction. Three distinct topological regions in the hadronic final state are thus defined by the azimuthal angle difference $\Delta\phi$ between the directions, in the plane transverse to the beam, of the leading object and that of any charged hadron in the event. Hadron production in the “toward” region with $|\Delta\phi| < 60^\circ$ and in the “away” region with $|\Delta\phi| > 120^\circ$ is expected to be dominated by the hard parton-parton scattering and radiation. The UE structure can be best studied in the “transverse” region with $60^\circ < |\Delta\phi| < 120^\circ$.

UE dynamics is studied through the confrontation of models with the data. In this paper, MC predictions for charged particle production are compared after full detector simulation to the data, uncorrected for detector effects. The predictions for inelastic events are calculated using several tunes of the PYTHIA programme, version 6.420 [3, 8], which provide different descriptions of the non-diffractive component: D6T [9, 10], DW [10], Pro-Q20 [11], Perugia-0 (P0) [12], and CW, the last being adapted from the DW tune as described below. They differ, in particular, in the implementation of the regularization of the formal $1/\hat{p}_T^4$ divergence of the leading order partonic scattering amplitude as the final state parton transverse momentum $\hat{p}_T$ approaches 0. In PYTHIA this divergence is regularized through the replacement $1/\hat{p}_T^4 \to 1/(\hat{p}_T^2 + \hat{p}_{T_0}^2)^2$. The energy dependence of the cutoff transverse momentum $\hat{p}_{T_0}$ is parameterized as $\hat{p}_{T_0}(\sqrt{s}) = \hat{p}_{T_0}(\sqrt{s_0}) \cdot (\sqrt{s}\ /\sqrt{s_0})^\epsilon$, where $\sqrt{s_0}$ is the reference energy at which $\hat{p}_{T_0}$ is determined and ϵ is a parameter describing the energy dependence. CDF studies [4, 5] favour a value of $\hat{p}_{T_0} = 2.0\,\text{GeV}/c$ for $\sqrt{s_0} = 1.8\,\text{TeV}$. Because a single value of $\hat{p}_{T_0}$ is used to regularize both MPI and hard scattering, this parameter governs the description of the amount of MPI in the event. More MPI activity is predicted for smaller values of $\hat{p}_{T_0}$.

All tunes considered in this paper are consistent with the UE measurements by CDF. Tunes DW, P0, and Pro-Q20 use $\epsilon = 0.25$, in agreement with CDF data at $\sqrt{s} = 630\,\text{GeV}$ and 1.8 TeV. Tune D6T uses the value $\epsilon = 0.16$, which is motivated by the energy dependence of charged particle multiplicities measured by the UA5 collaboration at the Sp$\bar{\text{p}}$S collider [13]. For tune CW, $\hat{p}_{T_0}$ is decreased to $1.8\,\text{GeV}/c$ and ϵ is increased to 0.30, while the parameters controlling the relative weighting of possible color connections in the matrix elements are changed back from the DW values to the PYTHIA defaults; these changes lead to a large increase of the simulated MPI activity at $\sqrt{s} = 0.9$ TeV and to an increase of a few percent at the Tevatron with $\sqrt{s} = 1.8$ TeV, while remaining consistent with the CDF results. The parton distribution functions used to describe the interacting protons are the CTEQ6LL set for D6T and the CTEQ5L set for the other tunes [14, 15]. Tunes P0 and Pro-Q20 use LEP results to describe hadron fragmentation at high z, where z denotes the fraction of the parton momentum carried by a final state particle. Tune P0 uses the new PYTHIA MPI model [16], which is interleaved with parton showering.

2 Detector Description and Event Selection

A detailed description of the CMS detector can be found in [17]; features most relevant for the present analysis are described in the following. A right-handed coordinate system is used with the origin at the nominal interaction point (IP). The x axis points to the centre of the LHC ring, the y axis is vertical and points upward, and the z axis is parallel to the anti-clockwise beam direction. The azimuthal angle ϕ is measured with respect to the x axis in the xy plane and the polar angle θ is defined with respect to the z axis.

The pixel and silicon strip tracker, immersed in the axial 3.8 T magnetic field provided by the 6 m diameter superconducting solenoid, measures charged particle trajectories in the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln(\tan(\theta/2))$. The p_T resolution for 1 GeV/c charged particles is between 0.7% at $\eta = 0$ and 2% at $|\eta| = 2.5$ [17]. The modules composing the tracker system were aligned with cosmic ray data taken prior to LHC commissioning, with a precision of 3–4 μm in the barrel region [18].

Three subsystems were involved in the trigger of the detector readout: the forward hadron calorimeter (HF), the Beam Scintillator Counters (BSC) [17, 19], and the Beam Pick-up Timing for eXperiments (BPTX) [17, 20]. The steel–quartz-fibre HF covers the region $2.9 < |\eta| < 5.2$. The two BSCs, each of which consists of a set of 16 scintillator tiles, are located along the beam line on each side of the IP at a distance of 10.86 m and are sensitive in the range $3.23 < |\eta| < 4.65$; they provide information on hits and coincidence signals with an average detection efficiency of 96.3% for minimum ionizing particles and a time resolution of 3 ns, compared to a minimum inter-bunch spacing of 25 ns. The two BPTX devices, which are located around the beam pipe at a distance of 175 m from the IP, are designed to provide precise information on the structure and timing of the LHC beams, with a time resolution better than 0.2 m. The data analyzed in this paper were selected by requiring a signal in both BSC counters, in coincidence with BPTX signals from both beams. During data taking, interaction rates were typically 11 Hz and the probability for multiple inelastic collisions to occur in the same proton bunch crossing was less than 2×10^{-4}.

The event selection requires one reconstructed primary vertex [21] with z coordinate within 15 cm of the centre of the beam collision region, of which the rms size is about 4 cm. Three or more tracks must be identified as originating at the vertex. Table 1 gives the numbers of events that pass these selection criteria. A study of data collected with non-colliding beams showed that beam-induced backgrounds are negligible.

Kinematic selections are based on the transverse momentum of the leading charged particle or of the leading track-jet, which must be reconstructed with pseudorapidity $|\eta| < 2$. The leading charged particle, or "leading track", must be reconstructed in the tracking detector. The leading track-jet is defined using the SISCone algorithm [22] as implemented in the fastjet package [23] with a clustering radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.5$. Only charged particles reconstructed

Table 1: Numbers of events in the data satisfying the selection criteria, and corresponding cumulative event fractions in the data and for the simulation based on PYTHIA with tune D6T. In the lower part of the table, the effects of various selection cuts applied to the leading object with $|\eta| < 2$ are given, each fraction being given with respect to the previous cut.

Event selection	Data [nb. events]	Data [%]	MC [%]
triggered	255 122	100	100
+ 1 primary vertex	239 038	93.7	92.9
+ 15 cm vertex z window	238 977	93.7	92.8
+ at least 3 tracks associated	230 611	90.4	88.7
leading track, $p_T > 0.5\,\text{GeV}/c$	216 215	93.8	93.2
$p_T > 1.0\,\text{GeV}/c$	131 421	60.8	55.0
$p_T > 2.0\,\text{GeV}/c$	28 210	21.5	19.5
leading track-jet, $p_T > 1.0\,\text{GeV}/c$	155 005	67.2	62.9
$p_T > 3.0\,\text{GeV}/c$	24 928	16.1	15.9

Table 2: Numbers of tracks in the selected event sample for successive track selection criteria, and corresponding fractions in the data and for the simulation based on PYTHIA with tune D6T. Each fraction is given with respect to the previous selection cut.

Track selection	Data [nb. tracks]	Data [%]	MC [%]
reconstruction algorithm	4 004 923	100	100
+ $p_T > 0.5\,\text{GeV}/c$	1 707 998	42.6	44.0
+ $|\eta| < 2.5$	1 689 910	98.9	98.7
+ $|\eta| < 2$	1 399 344	82.8	81.5
+ $d_{xy}/\sigma(d_{xy}) < 5$	1 235 193	88.3	88.8
+ $d_z/\sigma(d_z) < 5$	1 204 979	97.6	97.9
+ $\sigma(p_T)/p_T < 5\%$	1 168 530	97.0	96.9
Total	1 168 530	29.2	29.8

in the tracker, with $p_T > 0.5\,\text{GeV}/c$ and $|\eta| < 2.5$, are used to define the track-jet. No further correction is applied to the track-jet p_T. The η range of the charged particles used to define the track-jet ($|\eta| < 2.5$) is chosen to be wider than that used for the UE analysis ($|\eta| < 2$) in order to avoid a kinematic bias. A simulation-based study of jets with $p_T > 5\,\text{GeV}/c$ indicates that track-jets in CMS are found with high efficiency and good angular and energy resolutions [24]; this has been verified for softer jets in the present analysis. The results of selection cuts on the leading track and leading track-jet p_T are given in Table 1.

A detailed simulation of the CMS detector response was performed, based on the GEANT4 package [25] with event simulation using PYTHIA tune D6T. The position and shape of the beam interaction region were adjusted to agree with the data [21]. Simulated events were processed and reconstructed in the same manner as collision data, and the results of the simulation are also reported in Table 1.

Table 3: Systematic uncertainties on track selection and reconstruction (see description in text). The uncertainties, expressed in %, are quoted for characteristic values of variables used for UE studies in the transverse region. For the first two variables, p_T designates the minimal value of the track-jet p_T; for the last three variables, events with a leading track-jet with $p_T > 3\,\text{GeV}/c$ are selected.

	track sel.	tracker align.	tracker mater.	bg. cont.	trigger	dead ch.	beam spot	total
$d^2N_{ch}/d\eta d(\Delta\phi)$ ($p_T = 3.5\,\text{GeV}/c$)	0.3	0.3	1.0	0.8	0.6	0.1	0.5	1.8
$d^2\Sigma p_T/d\eta d(\Delta\phi)$ ($p_T = 3.5\,\text{GeV}/c$)	0.4	0.3	1.0	0.8	1.1	0.1	0.5	1.8
dN_{ev}/dN_{ch} ($N_{ch} = 4$)	0.6	0.6	1.2	1.0	1.2	0.2	0.6	2.3
$dN_{ev}/d\Sigma p_T$ ($\Sigma p_T = 4.5\,\text{GeV}/c$)	0.5	0.2	0.6	0.5	1.2	0.2	0.4	1.6
dN_{ch}/dp_T ($p_T = 1\,\text{GeV}/c$)	0.8	0.6	1.0	0.8	1.0	0.2	0.5	2.0

3 Track Selection and Systematic Uncertainties

A charged particle track is selected for the UE analysis if it originates from the primary vertex and is reconstructed in the pixel and silicon strip tracker with transverse momentum $p_T > 0.5\,\text{GeV}/c$ and pseudorapidity $|\eta| < 2$. A high purity reconstruction algorithm (see Section 3 of [21]) is used, which keeps low levels of fake and poorly reconstructed tracks. To decrease contamination by secondary tracks from decays of long-lived particles and photon conversions, the distance of closest approach between track and primary vertex is required to be less than five times its estimated uncertainty, both in the transverse plane, $d_{xy}/\sigma(d_{xy}) < 5$, and along the z axis, $d_z/\sigma(d_z) < 5$. Poorly measured tracks are removed by requiring $\sigma(p_T)/p_T < 5\%$, where $\sigma(p_T)$ is the uncertainty on the transverse momentum measurement. In the selected track sample with $|\eta| < 2$, these cuts result in a background level of 3%, 1% from K^0_S and Λ^0 decay products and 2% from fake tracks.

The numbers of tracks accepted at the different selection steps and the corresponding fractions are given in Table 2, together with the fractions calculated using simulated data. Agreement is observed at the percent level between data and simulation, for all selection steps.

Several systematic uncertainties may affect the comparison of models with the data. The sources of these uncertainties include the implementation in the simulation of track selection criteria, tracker alignment and tracker material content, background contamination, trigger conditions, and run-to-run variations of tracker and beam conditions.

The uncertainty in the simulation of track selection has been evaluated by applying various sets of criteria and comparing their effects to the data and to simulated events.

The tracking performance depends on occupancy; because efficiencies and fake rates computed using different models are found to be consistent within statistical uncertainties, no systematic uncertainty due to occupancy variation is assigned. The effects of tracker misalignment are found to change the results by less than 1%. The description in the simulation of inactive tracker material has been found to be adequate within 5%; increasing the material densities by 5% in the simulation induces a change smaller than 1% in the tracking efficiency and has no significant effect on background rates.

The simulation has been found to underestimate K^0_S and Λ^0 production as well as photon conversion rates. These discrepancies induce changes of less than 0.5% in the background contamination. Increasing the combinatorial background by a conservative 30% leads to a combined 0.8% uncertainty due to background description.

The uncertainty related to the simulation of the BSC-based trigger is taken to be half of the difference between the distributions obtained with and without trigger simulation. This estimate of the trigger-related systematic uncertainty was verified by means of HF-triggered events for which the BSCs had not generated a trigger.

The number of inactive tracker channels changes from run to run; reproducing this effect in the simulation induces a change of less than 0.5% in the observed distributions. The beam collision region is not perfectly centred within the detector, and its position changes from run to run; simulating different beam spot positions, consistent with those observed in different runs, leads to a 0.5% uncertainty.

The systematic uncertainties are largely independent from one another, but they are correlated among data points in the experimental distributions. Table 3 gives the main uncertainties for selected events with a leading track-jet with $p_T > 3\,\mathrm{GeV}/c$, for characteristic values of variables used for UE studies in the transverse region. Most uncertainties increase by typically 50% when the selection requires a leading track with $p_T > 2\,\mathrm{GeV}/c$.

4 Results

Predictions from the various PYTHIA models, after full detector simulation, are compared to the data. The scale of an interaction at parton level is defined by the p_T value of the leading object, either a track or a track-jet with $|\eta| < 2$. As can be observed in Table 1, demanding a leading particle with $p_T > 2\,\mathrm{GeV}/c$ or a leading track-jet with $p_T > 3\,\mathrm{GeV}/c$ reduces the sample size by a similar factor of about 10.

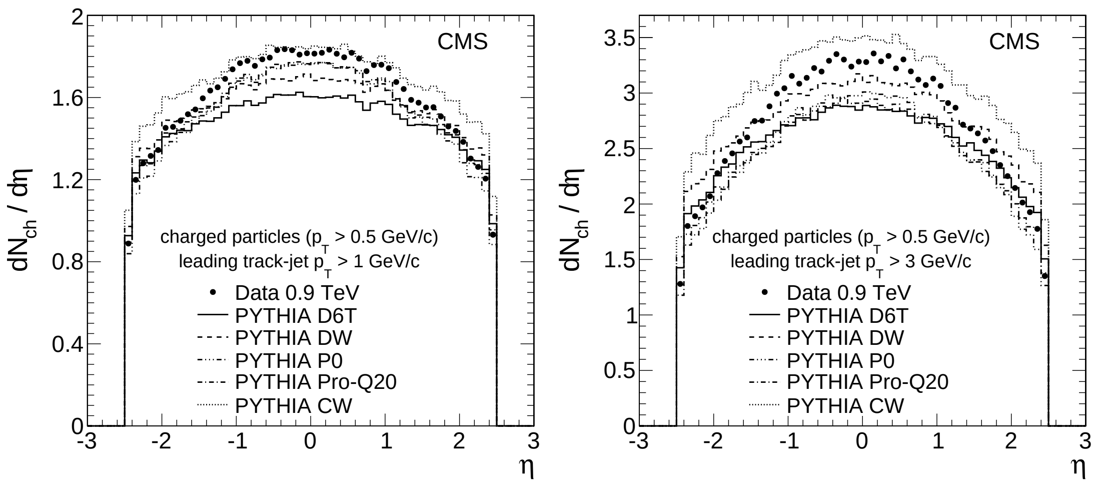

Figure 1: Average multiplicity, per unit of pseudorapidity, of charged particles with $p_T > 0.5\,\mathrm{GeV}/c$, as a function of η. The leading track-jet is required to have $|\eta| < 2$ and (left) $p_T > 1\,\mathrm{GeV}/c$, or (right) $p_T > 3\,\mathrm{GeV}/c$ (note the different vertical scales). Predictions from several PYTHIA MC tunes, including full detector simulation, are compared to the data.

Figure 1 presents, as a function of η, the average multiplicity N_{ch} per unit of pseudorapidity of charged particles with $p_T > 0.5\,\mathrm{GeV}/c$; for this figure, the track selection is extended to $|\eta| = 2.5$. Distributions are shown for two choices of the minimal value required for the p_T

of the leading track-jet. For a harder scale, the multiplicities are larger and charged particles with $p_T > 0.5\,\mathrm{GeV}/c$ are produced more centrally. The various PYTHIA tunes describe several features of the data: the overall normalization, the η dependence of particle production, and the effect of the leading track-jet p_T cut. However, no simulation describes perfectly all elements of the data, either in normalization or in shape. For both values of the minimal p_T of track-jets, the data show a significantly stronger η dependence than predicted by the PYTHIA tunes. Predictions of tune CW are too high in normalization, whereas those of tunes D6T, P0, and Pro-Q20 are generally too low, with DW being too low in the central region and too high at large $|\eta|$ values. The shape description is slightly better with tunes P0 and Pro-Q20. Similar observations are made when the selection criteria are applied to the leading track p_T. The observed features can be due to shortcomings in the description of parton fragmentation and radiation (essentially the toward and away regions), in the description of the UE (visible in the transverse region), or in both.

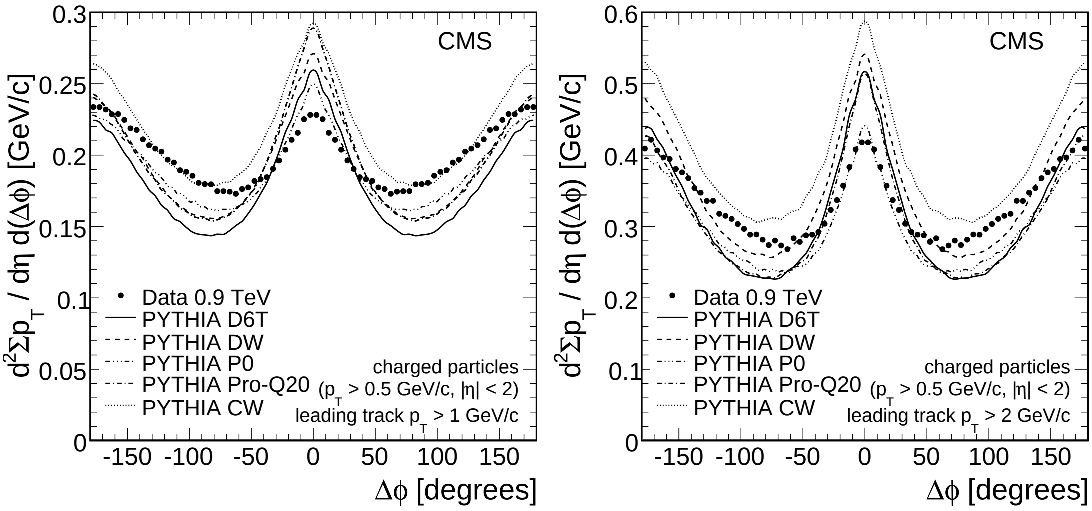

Figure 2: Average scalar sum of transverse momenta of charged particles with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$, per unit of pseudorapidity and per radian, plotted as a function of the azimuthal angle difference $\Delta\phi$ relative to the leading track (the measurements have been symmetrized in $\Delta\phi$). The leading track, which is excluded from the p_T sum, is required to have $|\eta| < 2$ and (left) $p_T > 1\,\mathrm{GeV}/c$, or (right) $p_T > 2\,\mathrm{GeV}/c$ (note the different vertical scales). Predictions from several PYTHIA MC tunes, including full detector simulation, are compared to the data.

The production of charged particles with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$ in the different topological regions and the quality of the MC description can be examined through the distribution of the azimuthal separation $\Delta\phi$ between the directions of the leading object and of any selected track. As an example, Fig. 2 presents the distribution of $\mathrm{d}^2\Sigma p_T/\mathrm{d}\eta\mathrm{d}(\Delta\phi)$, where $\sum p_T$ denotes the scalar sum of particle transverse momenta, excluding the leading track at $\Delta\phi = 0$. The events are selected with two different values of the leading track minimal p_T. The characteristic features of two-jet parton-parton production with underlying activity are observed. Although the leading track p_T is not included in the calculation, the average $\sum p_T$ in the toward region, $|\Delta\phi| < 60^\circ$, shows substantial activity due to parton fragmentation and radiation. Charged hadron production is also significant around the opposite direction, $|\Delta\phi| > 120^\circ$; this is attributed to the fragmentation of the second outgoing parton. In the transverse region with $60^\circ < |\Delta\phi| < 120^\circ$, hadron production is depleted but it is nonzero, a feature that is attributed mainly to MPI. Similar features of the event structure are observed for the average track multiplicity and for selections based on the leading track-jet p_T.

In the toward region, all PYTHIA tune predictions are significantly above the data, except for tune P0 with the scale $p_T > 2\,\mathrm{GeV}/c$. The poor description by tune Pro-Q20 compared to that of P0 may appear surprising since both use LEP results on jet fragmentation. A difference between these tunes is that P0 incorporates newer MPI modeling and p_T ordered showering. Model descriptions are better for the away region, except for the CW and DW tunes, both of which are significantly above the data when the scale is large.

The transverse region is most relevant for understanding UE properties. Here, the best tunes are CW and DW. The predictions of the CW model are slightly too high, especially for the higher p_T scale, and those of DW slightly too low; predictions of the other tunes are even lower. In the following, studies of the UE using the transverse region will focus on the comparison with data of the predictions of the CW and DW tunes.

Figures 3 and 4 provide detailed information on the production of charged particles with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$ in the transverse region with $60^\circ < |\Delta\phi| < 120^\circ$. Figure 3 presents the distributions of the average multiplicity, $\mathrm{d}^2N_{\mathrm{ch}}/\mathrm{d}\eta\mathrm{d}(\Delta\phi)$, and of the average scalar momentum sum, $\mathrm{d}^2\Sigma p_T/\mathrm{d}\eta\mathrm{d}(\Delta\phi)$, as a function of the scale provided by the p_T of the leading track or of the leading track-jet. At low p_T of the leading object, the multiplicity and the scalar $\sum p_T$ rise rapidly with p_T, which is attributed to MPI. This fast rise is followed by a slower increase for leading tracks with $p_T \gtrsim 3\,\mathrm{GeV}/c$ (left plots) or leading track-jets with $p_T \gtrsim 4\,\mathrm{GeV}/c$ (right plots), attributed to a saturation of MPI, plus additional radiation; as expected, a similar scale is provided by a lower p_T value for a leading track than for a leading track-jet. The behaviour of the data is reproduced by both the CW and DW tunes, as well as by the other PYTHIA tunes (not shown), with a better description by CW in the low p_T region.

The distributions of charged particle multiplicity, of scalar $\sum p_T$, and of particle p_T are presented in Fig. 4 for events selected with a leading track-jet with $p_T > 3\,\mathrm{GeV}/c$. The CW and DW tunes bracket the data over most of the experimental range, and they describe the various dependences rather well. Similar behaviours are observed for selections based on the leading track p_T.

The information is summarized in Fig. 5, which presents the ratio of the MC predictions to the measurements, for the variables presented in Figs. 3 and 4. The shape of the steeply falling hadron p_T spectrum is well described by all tunes, in particular the P0 tune, which achieves good agreement in the high-momentum tail because of its hard p_T spectrum. The CW and DW tunes globally describe the measurement of hadron production in the transverse region best, both in normalization and in shape, with the CW predictions generally higher than the data and the DW predictions lower. A small dependence on the choice of the leading object is observed, with a preference for CW in the case of a leading track-jet and for DW in the case of a leading particle (not shown). The predictions of tune D6T are too low and generally the least consistent with the data. The predictions of tunes Pro-Q20 and P0 tend to lie between the predictions of tunes D6T and DW.

5 Summary and Conclusions

This paper describes a study of the production of hadrons with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$ at the LHC, in proton-proton collisions at $\sqrt{s} = 0.9\,\mathrm{TeV}$. Event selection required the presence of a hard scale, provided by the transverse momentum of the leading charged particle or of the leading track-jet. The minimal value of the scale was chosen in the range 1 to $3\,\mathrm{GeV}/c$. Particular attention has been devoted to the transverse region, defined by the difference in azimuthal angle between the leading object and charged particle directions, $60^\circ < |\Delta\phi| < 120^\circ$,

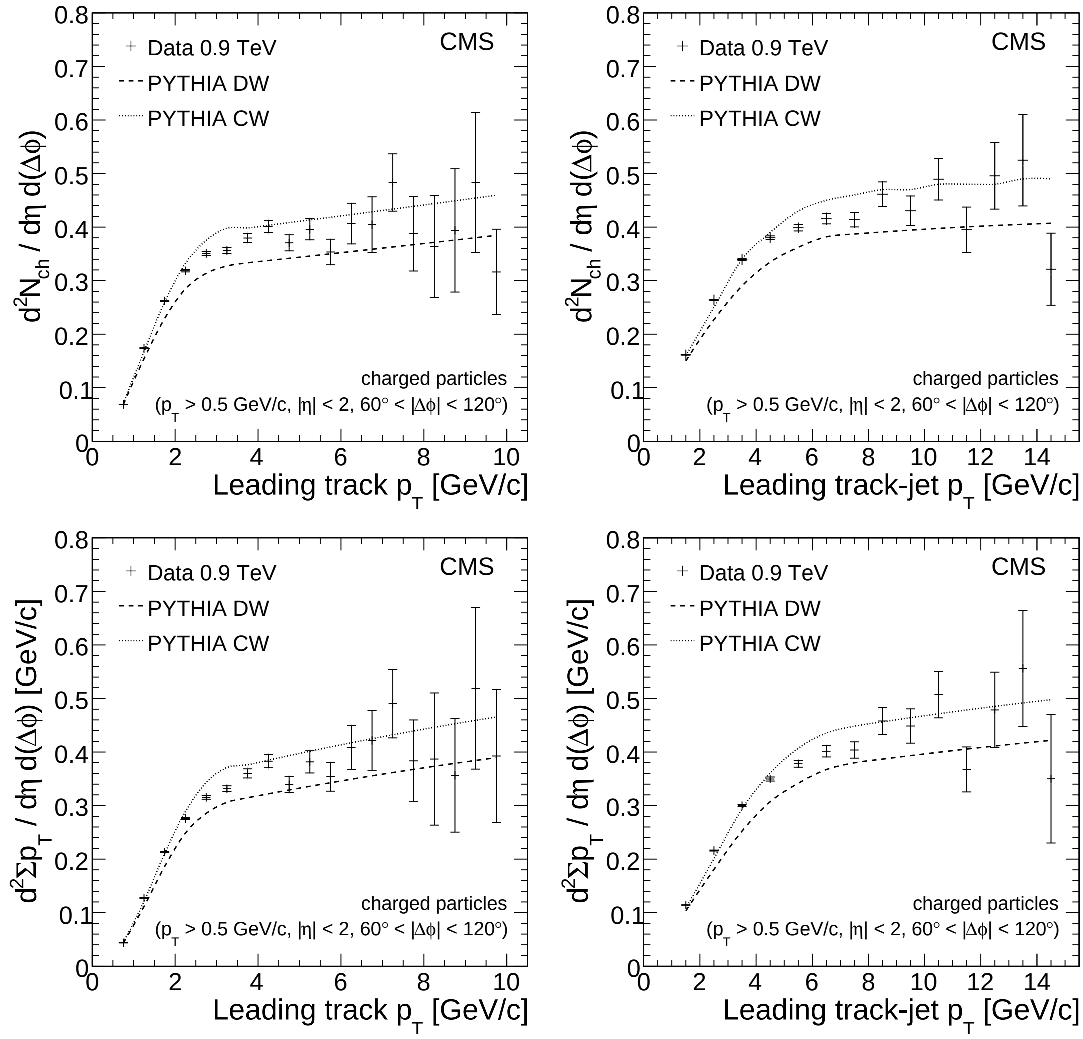

Figure 3: For charged particles with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$ in the transverse region, $60^\circ < |\Delta\phi| < 120^\circ$: (upper plots) average multiplicity, and (lower plots) average scalar $\sum p_T$, per unit of pseudorapidity and per radian, as a function of (left plots) the p_T of the leading track, and (right plots) the p_T of the leading track-jet. The inner error bars indicate the statistical uncertainty and the outer error bars the total experimental uncertainty (statistical and systematic uncertainties added in quadrature); statistical errors dominate. Predictions of the DW and CW PYTHIA MC tunes, including full detector simulation, are compared to the data.

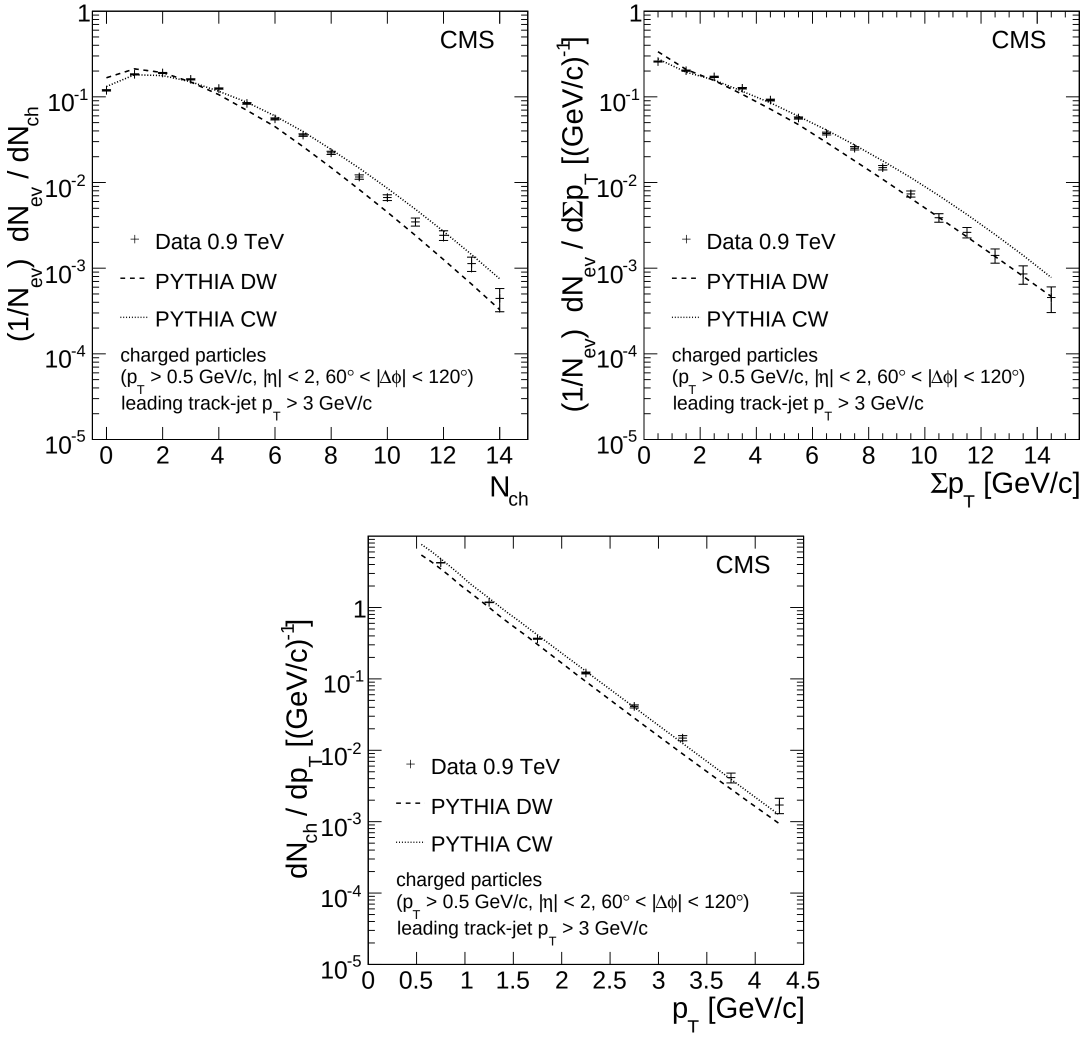

Figure 4: For charged particles with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$ in the transverse region, $60^\circ < |\Delta\phi| < 120^\circ$: (upper left) normalized multiplicity distribution; (upper right) normalized scalar $\sum p_T$ distribution; (bottom) p_T spectrum. The leading track-jet is required to have $|\eta| < 2$ and $p_T > 3\,\mathrm{GeV}/c$. The inner error bars indicate the statistical uncertainty and the outer error bars the total experimental uncertainty (statistical and systematic uncertainties added in quadrature); statistical errors dominate. Predictions of the DW and CW PYTHIA MC tunes, including full detector simulation, are compared to the data.

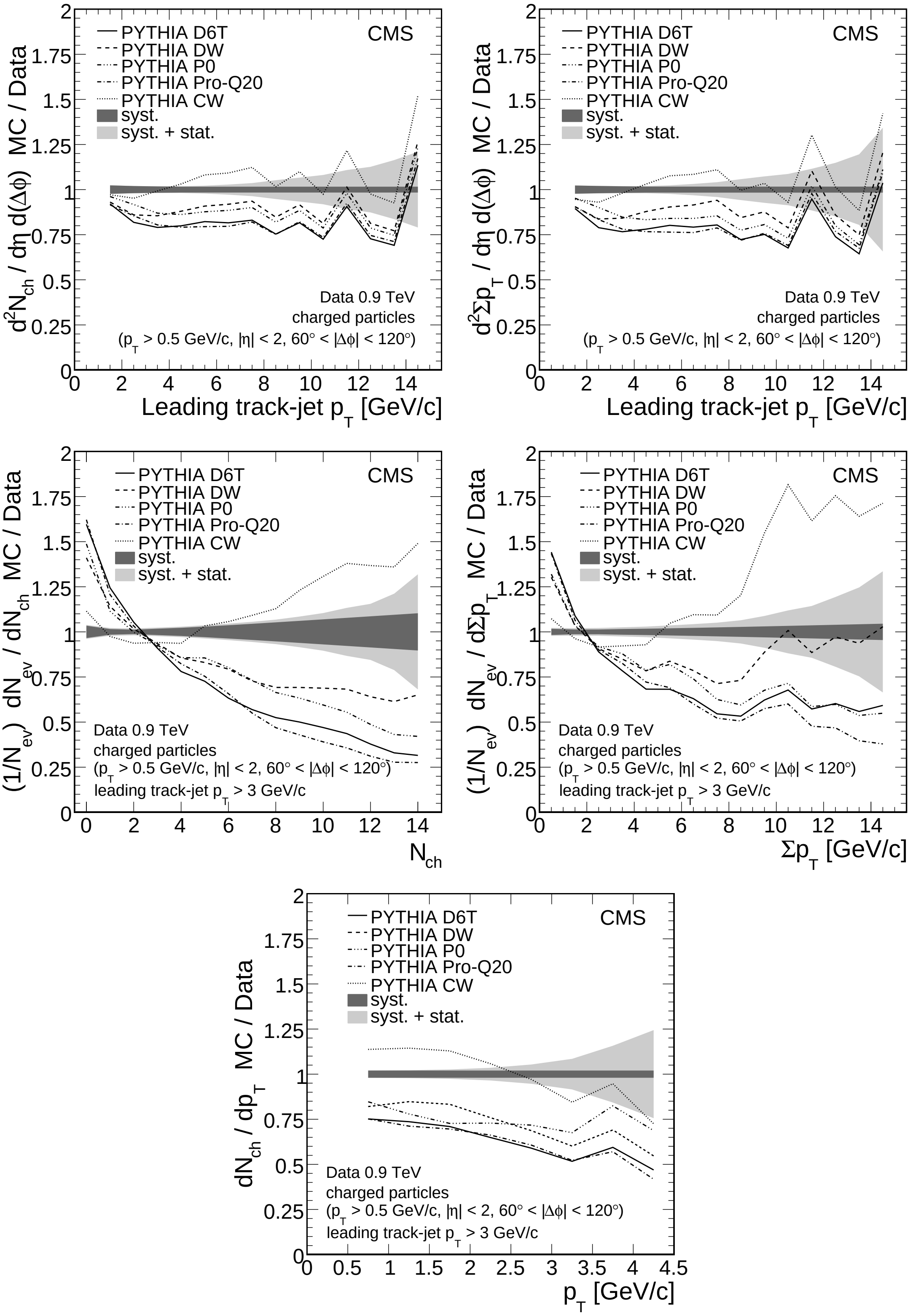

Figure 5: Ratios of various MC predictions, including full detector simulation, to the measurements of hadrons with $p_T > 0.5\,\mathrm{GeV}/c$ and $|\eta| < 2$ in the transverse region, $60^\circ < |\Delta\phi| < 120^\circ$: (from top left to bottom) average multiplicity of charged particles, as a function of the leading track-jet p_T (cf. Fig. 3, upper right); average scalar $\sum p_T$, as a function of the leading track-jet p_T (cf. Fig. 3, lower right); distribution of the charged particle multiplicity (cf. Fig. 4, upper left); distribution of the scalar $\sum p_T$ (cf. Fig. 4, upper right); p_T spectrum (cf. Fig. 4, bottom). The inner bands correspond to the systematic uncertainties and the outer bands to the total experimental uncertainty (systematic and statistical uncertainties added in quadrature).

which is most appropriate for the study of the underlying event.

The predictions of several PYTHIA MC models, after full detector simulation, have been compared to the data. The models are all consistent with data taken at the Tevatron at $\sqrt{s} = 1.8$ TeV, but they differ in the implementation of radiation, fragmentation, and multiple parton interactions. They describe general features of the data. In the transverse region most tunes predict too little hadronic activity. An important parameter of simulation tuning in the PYTHIA framework is the centre-of-mass energy dependence of the low $\hat{p}_{T_0}$ cutoff aimed at regularizing singularities in hard scattering and MPI. The present data favour an energy dependence of this parameter along the lines of PYTHIA tune DW ($\epsilon = 0.25$) or even stronger ($\epsilon = 0.30$, as in tune CW). Lower values of ϵ, as in tune D6T ($\epsilon = 0.16$), are disfavoured.

The present measurements, together with results from Sp$\bar{\text{p}}$S, Tevatron, and RHIC, as well as future LHC results at $\sqrt{s} = 7$ and 14 TeV, are expected to help in understanding better the properties of the underlying event and of multiple parton interactions in hadron-hadron scattering at high energy. This is essential for precision measurements of Standard Model processes and for the search for new physics at the LHC.

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