RECENT CMS RESULTS ON SOFT AND SMALL-x QCD PHYSICS*

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We present latest results of soft and small-x QCD measurements with the CMS experiment, such as minimum bias, underlying event physics, and studies on forward jet production.

1. Introduction

Quantum chromodynamics (QCD), the theory of strong nuclear interactions, is undoubtedly a very rich and successful theory. There are interesting phenomena in nuclear interactions which have yet to be seen, phenomena that are ultimately related to the properties of color confinement and asymptotic freedom of the strong interactions. These effects can take place in special corners of phase space accessible at the Large Hadron Collider (LHC). More concretely, it is not clear whether a gluon–gluon recombination mechanism takes place at low values of the fraction of the nucleon momentum x carried by its partonic constituents. The said mechanism is believed to slow down the rapid growth of the nucleon's structure function at very small values of x.

On the other hand, we have to refine our understanding of the underlying dynamics in low-momentum exchange processes in hadronic collisions. The description of these effects rely on phenomenological models, whose parameters are tuned based on fits to data. Dedicated measurements provide valuable inputs for Monte Carlo event generators, which are of great importance for precision measurements of Standard Model processes and searches for new physics at the LHC.

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In this context, we briefly discuss the following recent results by the CMS experiment:

— Very forward inclusive jet cross-section measurement in p–Pb collisions at $\sqrt{s}_{NN} = 5.02$ TeV [1];

— Measurement of charged particle spectra in minimum-bias events from p–p collisions at 13 TeV [2];

— Measurement of the underlying event activity in inclusive Z-boson production in p–p collisions at 13 TeV [3].

2. Very forward inclusive jet cross section in p–Pb collisions

The CMS experiment [4] is equipped with the CASTOR electromagnetic and hadronic calorimeter, which extends the measurable jets pseudorapidity acceptance up to $-6.6 < \eta < -5.2$ with approx. $p_T \geq 4$ GeV. A study of jets in CASTOR in p+Pb collisions possesses unique sensitivity to non-linear evolution effects due to the very forward acceptance ($x \sim 10^{-6}$) and the enhancement of the parton densities in the ion (scales with the number of nucleons as $\sim A^{1/6}$). The measurement of forward inclusive jet cross section is done for the p+Pb (proton towards CASTOR) and the Pb+p (Pb-ion towards CASTOR) configurations. The p+Pb configuration is ideal to probe small-x physics.

The sample was collected in p–Pb collisions at the c.o.m. of $\sqrt{s}_{NN} =$ 5.02 TeV in the lab frame (proton beam energy of 4 TeV and 1.6 TeV/nucleon for the Pb beam) using a minimum bias trigger. To suppress the contribution from diffractive and photon-induced processes, a requirement of minimum one calorimeter tower with energy above 4 GeV in $3 < |\eta| < 5$ on both sides is applied.

The main result of the study is the differential cross section as a function of the jet energy deposited in CASTOR. The cross sections are unfolded to particle level jets. The leading systematic uncertainty comes from the CASTOR jet energy scale, followed by uncertainties associated to the model dependence from the unfolding procedure and the alignment and calibration corrections. HIJING, EPOS and QGSJetII event generators are compared to data; they each have a different treatment for the non-linear evolution effects. HIJING describes the data very well for the p+Pb configuration, while EPOS and QGSJetsII progressively underestimate the cross section with increasing energy. In the Pb+p configuration, HIJING and EPOS give a reasonable description of the data up to normalization.

To enhance the model discrimination power, the ratio of the p+Pb and Pb+p spectra is measured as a function of the jet energy. The ratio nearly cancels the energy scale uncertainty, leaving the model dependence from the
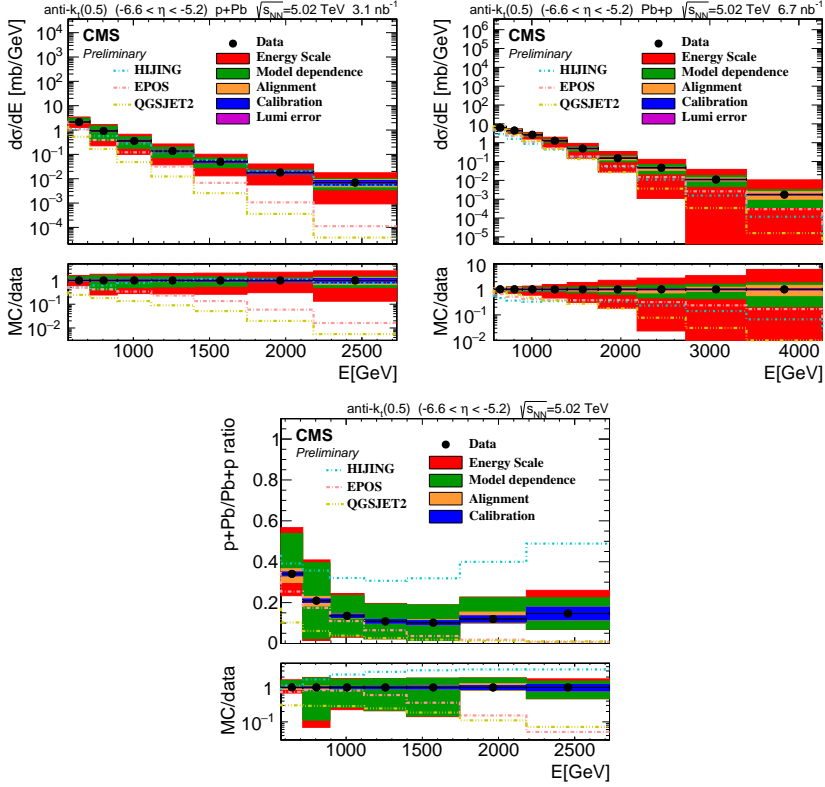
Fig. 1. The differential cross section as a function of the jet energy in CASTOR for the $p+$Pb configuration (left), the Pb$+p$ configuration (right), and the ratio of the differential cross section in $p+$Pb to Pb$+p$ as a function of the jet energy (bottom). Figures were extracted from Ref. [1].

unfolding procedure as the leading systematic uncertainty. This observable has the caveat that the ratio is performed on configurations boosted with respect to each other. HIJING describes the shape well, but is off by a factor of ~ 2 due to the poor Pb$+p$ description. EPOS and QGSJetII are off in shape and show a large discrepancy at increasingly large energies.

3. Measurement of charged particle spectra in minimum-bias events at 13 TeV

Particle production without any selection bias arising from the requirement of the presence of a hard scattering process is known as minimum bias (MB). The bulk of these events occur at low momentum exchanges between the interacting partons inside the hadrons, where diffractive scattering or multiple partonic interactions (MPI) play a significant role.

One can characterize MB events by means of charged particle distributions. Charged particle distributions are measured for charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.4$ for events collected with the CMS MB trigger. The measured distributions are presented for different event data samples based on the calorimeter activity in the forward region by requiring the presence of at least one tower with energy above 5 GeV in the acceptance region $3 < |\eta| < 5$, and in some cases, with a veto condition for towers less than a given threshold value. The different event classes are as non-single diffractive enriched sample (NSD-enhanced) when there is calorimeter activity in both sides, as single diffractive enriched (SD-enhanced) when there is calorimeter activity on one side and a veto on the opposite side, and as inelastic when there is calorimeter activity on at least one side of CMS. The distribution labeled SD-One-Side enhanced sample corresponds to the symmetrized distribution constructed from the SD-minus and SD-plus enhanced samples.
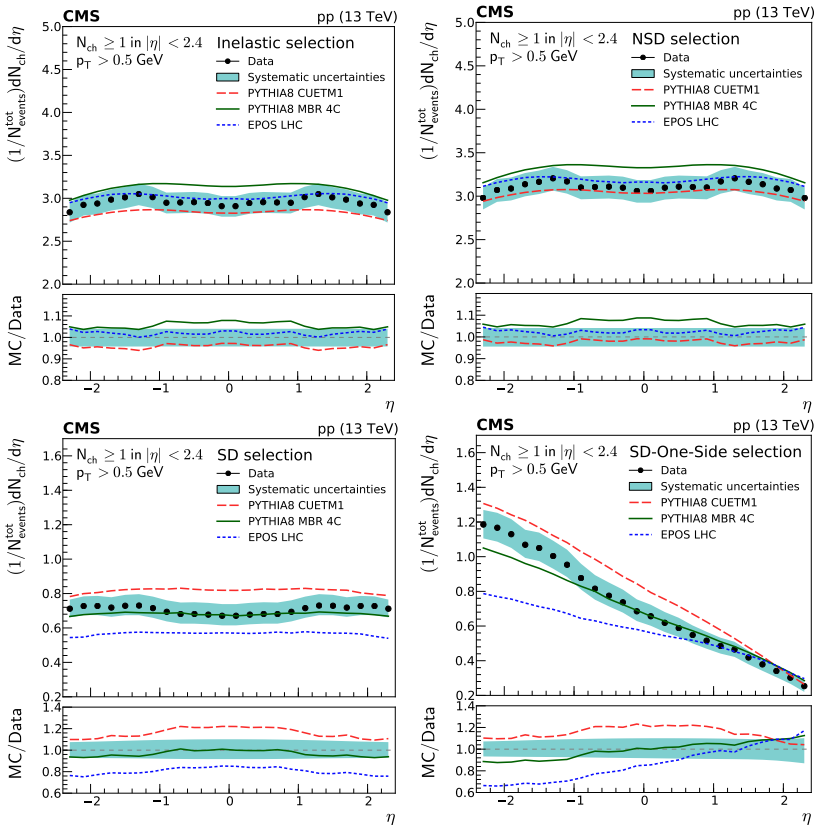

Fig. 2. Normalized differential charged particle multiplicity distributions as a function of pseudorapidity for the different sample selections. The error band represents the total systematic uncertainty. Figures were extracted from Ref. [2].

The normalized particle distribution is measured as a function of the charged particle pseudorapidity for the three different selections (see Fig. 2). The results are unfolded to particle level. PYTHIA8 CUETM1, PYTHIA8 MBR 4C and EPOS LHC results are compared to the data. PYTHIA8 MBR 4C describes reasonably well the data for the SD-enhanced samples, but overestimates the yield in central pseudorapidities for the non-diffractive samples. PYTHIA8 CUETM1 and EPOS LHC give a fair description for the non-diffractive samples, but they are off w.r.t. data for the SD-enhanced selection.

4. Measurement of the underlying event activity in inclusive Z-boson production in p–p collisions at 13 TeV

The underlying event (UE) is any activity stemming from beam–beam remnants and MPI. The UE produces particles carrying low transverse momentum, and are hard to disentangle from the initial state radiation (ISR) and final-state radiation (FSR) present in the hard scattering process.

The UE activity is quantified in terms of the charged particle multiplicity, as well as the scalar sum of the charged particles' transverse momenta, in different angular regions defined with respect to a clean hard scattering process probe, in this case the Z boson ($pp \rightarrow Z + X$), where the Z decays into a $\mu^+\mu^-$ pair. This process is theoretically well-understood, and has the additional advantage that FSR is not present. Muons satisfy $p_T^\mu > 20$ GeV, $|\eta^\mu| < 2.4$ and $81 < m_{\mu\mu} < 101$ GeV.

The charged particle activity relative to the Z-boson direction is studied in three angular regions labeled towards, transverse and away regions, which are respectively defined by $|\Delta\phi| < 60°$, $60° < |\Delta\phi| < 120°$ and $|\Delta\phi| > 120°$, where $\Delta\phi$ is the azimuthal angle separation between the charged particle and the dimuon direction. Charged particles are required to satisfy $p_T > 0.5$ GeV and $|\eta| < 2$ for the measured distributions.

The average particle density as a function of the dimuon transverse momentum is shown in Fig. 3. Combinations of MADGRAPH and POWHEG (which include ISR calculations for inclusive Z-boson production) interfaced with PYTHIA8 and HERWIG++ for parton shower, hadronization effects, and UE activity, are compared to data. These combinations give reasonable agreement in shape w.r.t. the data, with the POWHEG+HERWIG++ off in normalization by ~ 10–20%.
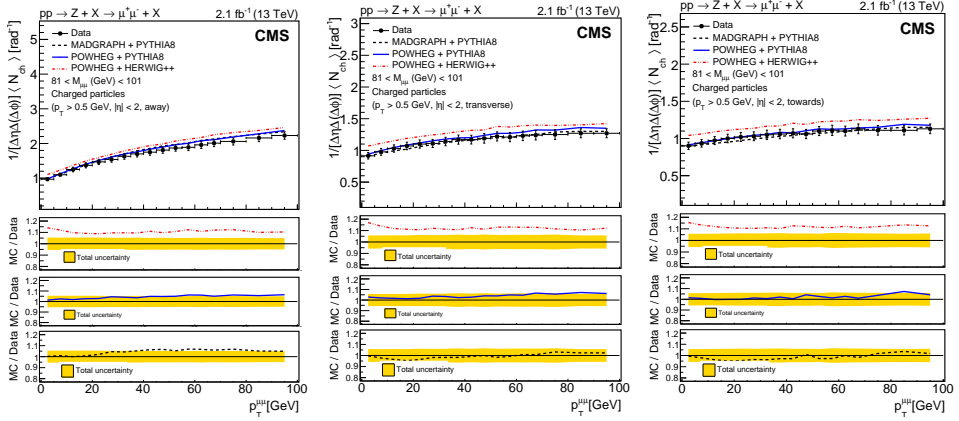
Fig. 3. Average charged particle density as a function of the dimuon transverse momenta in the away (left), transverse (center) and towards (right) regions. Figures were extracted from Ref. [3].

5. Conclusions

The LHC keeps enlarging our access to unexplored phase space to study strong interactions. $p+$Pb results need to be further interpreted for stronger assessments on potential saturation effects. Measurement of MB events and UE activity probe the dynamics of hadron production with increasing precision at various center-of-mass energies, which provide very important new inputs for MC tuning necessary for precision measurements of the Standard Model and searches for new physics.

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