The Compact Muon Solenoid Experiment
Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

05 October 2018 (v4, 12 October 2018)

QCD Soft and Forward Physics at CMS

Valentina Mariani for the CMS Collaboration

Abstract

We present recent results on minimum bias collisions, underlying event activity and double parton scattering using data recorded by CMS detector at the LHC. The results on the measurement of the underlying event using leading tracks, jets, and Drell-Yan processes are presented. Double parton scattering is investigated in several final states including vector bosons and multi-jets, and the results are compared to other experiments and to multi parton interaction (MPI) models tuned to recent underlying event measurements at CMS.

Presented at *QCD 18 21st International Conference in Quantum Chromodynamics*

QCD Soft and Forward Physics at CMS

V. Mariani on behalf of the CMS Collaboration

Università degli Studi di Perugia. Via Alessandro Pascoli 06123 Perugia PG

Abstract

We present recent results on minimum bias collisions, underlying event activity and double parton scattering using data recorded by the CMS detector at the LHC. The results on the measurement of the underlying event (UE) using leading tracks, jets, and Drell-Yan processes are presented. Double parton scattering is investigated in several final states including vector bosons, and the results are compared to other experiments and to multi parton interaction (MPI) models tuned to recent underlying event measurements at CMS.

Keywords:

1. Proton-proton cross section measurement

The total proton-proton (p-p) cross section can be identified as the sum of two terms: the elastic scattering contribution and the inelastic scattering contribution. The latter can be further factorised into four independent processes: the single diffractive (SD), the double diffractive (DD), the central diffractive (CD) and the non diffractive (ND) components. At the LHC energy scale about 20 % of the scattering processes count as elastic and the remaining 80 % can be addressed as inelastic interactions.

The CMS experiment measured the inelastic p-p cross section at a center of mass energy of $\sqrt{s} = 13$ TeV based on information from forward calorimetry, at pseudorapidities $3 < \eta < 5.2$ and $-6.6 < \eta < -3$ [1]. Defining M_x and M_y as the largest diffractive mass systems moving towards negative and positive pseudorapidity respectively, the phase space is defined in $M_x < 4.1$ GeV and $M_y < 13$ GeV. In other terms $\xi_x = \frac{M_x^2}{s}$ and $\xi_y = \frac{M_y^2}{s}$ and thus $\xi = \max(\xi_x, \xi_y)$. The cross section is then calculated as $\sigma = \frac{N_{int}(1-b_\xi)}{\varepsilon_\xi L}$ where N_{int} is the number of interactions, ε_ξ is the efficiency defined as the fraction of selected stable-particle events that fulfill the detector-level offline selection criteria, and the contamination b_ξ is the fraction of detector-level

offline selected events that are not part of the considered stable-particle phase space domain. The CMS experimental results are reported in Fig. 1 for two different phase space domains, compared to ATLAS results and many Monte Carlo predictions.

Figure 1: Proton-proton inelastic cross section measurements provided by the CMS experiment in two phase space domains ($\xi > 10^{-6}$ on the left and $\xi_x > 10^{-7}$ or $\xi_y > 10^{-6}$ on the right) are compared to different theoretical predictions. A general overestimation of data points is shown [1].

The cross section for diffractive dissociation events escaping detection is underestimated by the models and

this is reflected in a general overestimation of the fiducial cross section. Following a model-dependent extrapolation, the total inelastic cross section is measured as: $\sigma_{inel} = 71.26 \pm 0.06(stat.) \pm 0.47(sys.) \pm 2.09(lum.) \pm 2.72(ext.)$ mb.

2. Identified charged hadron spectra and charged particle distributions

Charged particle measurement in p-p collisions provides insight into the strong interaction in the non-perturbative regime. Strong interaction in the soft regime is typically phenomenologically described by QCD models implemented in Monte Carlo event generators with free parameters that can be constrained by such measurements. Furthermore, an accurate description of low-energy strong interaction processes is essential for simulating pp interactions and achieving a deeper knowledge of the proton structure for a better definition of the final state. Within the CMS collaboration it is important to mention two complementary measurements: the identified charged hadron spectra and the charged particle distributions at $\sqrt{s} = 13$ TeV [2], [3]. The former provides the transverse momentum (p_T) spectra of charged pions, kaons and protons. Particles are identified via their energy loss (dE/dx) in the silicon tracker for low p_T values, as shown in Fig.2, for low p_T values up to 0.1 GeV in $|y| < 1$.

Figure 2: The dE/dx distribution as a function of the p for different identified charged particles [2].

The results are compared to different Monte Carlo models. In particular in Fig. 3 the K/π (magenta) and the p/π (blue) ratios are shown. The increase of both particle yield ratios are well described only by PYTHIA8.

Fig. 4 (top) shows the average value of p_T for the different particle species as a function of the number of

Figure 3: Ratios of particle yields, K/π and p/π as a function of p_T . Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. The curves indicate predictions from PYTHIA 8, EPOS, and PYTHIA 6 [2].

tracks in the event. An increase of the $\langle p_T \rangle$ with particle mass emerges. Two different behaviours can be identified: at low-multiplicity data points are well described by the predictions, while the high-multiplicity region needs a tuning of baryon and/or strangeness production. The same data points are then compared to the previous measurements made by CMS at lower center-of-mass values, Fig. 4 (bottom), in order to show that the $\langle p_T \rangle$ seems to be independent from the center-of-mass energy.

The second analysis of the charged particle distributions selects charged particles with $p_T > 500$ MeV and $|\eta| < 2.4$. The pseudorapidity density distribution is reported in Fig.5, comparing data to different Monte Carlo (MC) predictions.

A good global agreement is shown, especially for the EPOS predictions, also due to the large systematic uncertainties on the measurement.

3. Underlying events

The underlying events (UE) surround the hard scattering of an hadronic interaction and can receive contributions from initial and final state radiation (ISR/FSR), QCD evolution or color reconnection and additional partonic interactions in the same collision. Measuring the UE is then crucial for a proper understanding of the interaction and for MC model tuning. Fig.6 shows the azimuthal plane region segmentations once the leading object is identified and defining $|\Delta\Phi|$ as the relative azimuthal distance between a charged particle and the leading object:

Figure 4: On the top the average transverse momentum of identified charged hadrons (pions, kaons, protons) in the range $|\eta| < 1$, as functions of the corrected track multiplicity for $|\eta| < 2.4$ is compared to the curves that indicate predictions from PYTHIA 8, EPOS, and PYTHIA 6. On the bottom the same data points compared to the previous measurement made by CMS at lower center-of-mass values [2].

Figure 5: Charged-hadron pseudorapidity densities for data (black dots) and various MC predictions [3]

- Toward: $|\Delta\Phi| < 60^\circ$ dominated by the hard scatter, thus insensitive to the UE
- Away: $|\Delta\Phi| < 120^\circ$ dominated by the recoil activ-

ity, thus insensitive to the UE

- Transverse: $60^\circ < |\Delta\Phi| < 120^\circ$ sensitive to the UE; the observables defined here are the primary focus of the UE measurements.

Figure 6: The azimuthal plane sections in the UE studies. The different regions are identified starting from the identification of the leading object of the event.

Furthermore the "trans-diff" region, defined as the difference between the trans-max and trans-min observables, represents the best configuration to study the UE. The observables that best describe the UE are the average multiplicity ($\frac{1}{\Delta\eta\Delta(\Delta\Phi)} < N_{ch} >$) and the scalar sum of p_T ($\frac{1}{\Delta\eta\Delta(\Delta\Phi)} < \sum p_T >$).

Two kinds of analyses have been done within the CMS Collaboration and the main difference between the two is the choice of the leading object.

For the former [4] the reference object is the leading charged particle or leading charged jet of the event. The leading charged particle (leading jet) is selected with $p_T > 0.5$ GeV (1 GeV) and the charged particles of the events are then reconstructed with $p_T > 0.5$ GeV and $|\eta| < 2$. In Fig.7 the scalar sum of p_T is reported in the trans-diff region; a typical feature is shown with a steep rise at low p_T and then a large plateau. The shape is reproduced quite well by all the MC models considered, except EPOS that fails at high p_T values.

Similarly, Fig.8 shows the strong rise of the UE activity as a function of the $\sqrt{s}$ as predicted by the various MC tunes. The steep rise is interpreted as the saturation of the multiple parton interactions with more and more central collisions.

The second analysis, [5], considers a di-muon system, coming from the Z decay, as reference object. Muons are selected if they satisfy the following requirements: $p_T > 10, 20$ GeV for leading and subleading muon respectively in $|\eta| < 2.4$ and with a di-muon mass

Figure 7: Comparisons of transDIF average energy densities to the various simulations as a function of the leading track p_T [4]

Figure 8: Comparisons of transAVE particle densities to various simulations at $\sqrt{s} = 0.9, 2.76, 7,$ and 13 TeV as a function of the leading jet p_T [4].

in the range $81 < m_{inv} < 101$ GeV. Once the di-muon system is reconstructed, tracks are considered in the analysis if $p_T > 0.5$ GeV and $|\eta| < 2$. The same observables are thus shown in Fig.9, while Fig.10 reports the UE activity as a function of the center-of-mass energy. None of these distributions exhibits the rise at low p_T present in the previous measurement. The reason is that selecting a di-muon system coming from the Z decay the energy regime of the event is already high enough to reach into the plateau region.

4. Double parton scattering

From the study of the topology of a proton-proton collision we know that even in a soft energetic regime the MPIs surround the main hard scatter. With the rising of the center-of-mass energy and the consequent increasing of the parton density within the protons, the

Figure 9: Comparisons in the transverse region of the average energy densities and the average multiplicity to various simulations as a function of the di-muon system p_T [5]

Figure 10: Comparisons in the transverse region of the average energy densities and the average multiplicity to various simulations at $\sqrt{s} = 1.96, 7,$ and 13 TeV as a function of the di-muon system p_T [5].

probability that more than one hard scatter occurs in the same p-p collision is not negligible. An event with two independent hard parton scatterings in the same p-p collision is addressed as double parton scattering (DPS) and a sketch of a typical DPS event is reported in Fig. 11.

Figure 11: A sketch of a typical DPS event resulting from a p-p collision.

A DPS event can be considered interesting per se, in order to deeply understand the collision mechanisms and the internal proton structure, but also as a background process in the search of new physics.

In the simplest case of two identical processes, and with the assumption of no longitudinal correlations between partons, the DPS cross section can be written as [6]:

$$\sigma_{DPS}^{incl}(s) = \frac{1}{2} \int d^2\beta (A(\beta))^2 (\sigma^{incl})^2 \quad (1)$$

where the factor 1/2 accounts for two identical processes and σ^{incl} is the cross section of the single parton scattering process. For a more simplified notation the term $\int d^2\beta (A(\beta))^2$, which includes all the unknown parton correlations in the transverse dimension, is usually indicated as the inverse of the effective cross section, so that the figure of merit of DPS becomes:

$$\sigma_{eff} = \frac{1}{2} \cdot \frac{(\sigma^{incl})^2}{\sigma_{DPS}^{incl}} \quad (2)$$

So far several measurements have been published by many experiments in different final states and at different center-of-mass energies but a deep understanding is still missing. In particular the large uncertainties that affect these measurements did not allow to draw final conclusions about the correlations between σ_{eff} and $\sqrt{s}$ or the parton momentum, as well as a clear picture of the partonic correlations. CMS published several results using data at $\sqrt{s} = 7, 8$ TeV ([7], [8], [9], [10]) but the only public analysis at $\sqrt{s} = 13$ TeV investigates the DPS production in the same sign WW (ssWW) final state [11].

The ssWW production can be considered as a golden channel for the DPS study because the lepton final state ($W \rightarrow \ell\nu$, with $\ell = e, \mu$) provides a very good signal purity and, furthermore, at the LHC energy the single parton scattering (SPS) production is suppressed requiring the same sign, so that $\sigma_{SPS} \sim \sigma_{DPS}$. The diagrams of DPS and SPS events are reported in Fig. 12; as shown the key DPS signatures are the uncorrelated WW production and the absence of associated jets in the final state.

Several background processes can mimic the signal production, either because one of the lepton in the final state is out of the experimental acceptance or misreconstructed (such as WZ, ZZ, $W\gamma$) or, even if there is not a direct production of two same sign leptons, the contribution of fake leptons is not negligible because of the huge cross section (DY, W+jets, QCD, TTjets).

The analysis is performed on two flavour final states: $\mu^\pm\mu^\pm$ and $e^\pm\mu^\pm$. Since after the strategy application the

Figure 12: On the left the ssWW production via DPS mechanism, and on the right the various configurations for the ssWW production via SPS.

main background process remains the WZ, a boosted decision tree (BDT) is trained against the WZ in order to enhance the signal. The BDT classifier output is reported in Fig. 13 divided in lepton flavour and charge.

Figure 13: BDT classifiers reported divided in lepton flavour and charge. Data points (in black) result in a good agreement with the MC processes included in the analysis [11].

For the first time the σ_{DPS} has been measured in the ssWW final state as $\sigma_{DPS} = 1.09^{+0.50}_{-0.49}$ pb with an observed significance of 2.23σ . In spite of the small sensitivity of the direct measurement this is the most accurate result so far in this channel.

5. Conclusion

An overview of some representative soft QCD measurements made within the CMS Collaboration at

$\sqrt{s} = 13$ TeV has been presented. Globally a good understanding of the non perturbative regime has been achieved, thanks to high precision and detailed analysis techniques and very advanced developments in MC tuning. Several studies proved the importance of the introduction of multiple parton interactions in the description of the p-p collision mechanisms and, furthermore, that the double parton scattering is an important tool for the investigation of the proton structure and parton correlations. Not everything has been explained, however, and more and more analyses are ongoing in order to improve the actual MC models and remedy the inconsistencies between data and MC that still persist, particularly in the high-multiplicity regime.

References

- [1] "Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV", The CMS Collaboration, JHEP 07 (2018) 161
- [2] "Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s} = 13$ TeV", The CMS Collaboration, Phys. Rev. D 96, 112003 Published 5 December 2017
- [3] "Measurement of charged particle spectra in minimum-bias events from proton-proton collisions at $\sqrt{s} = 13$ TeV." The CMS Collaboration, Eur. Phys. J. C 78 (2018) 697
- [4] "Underlying Event Measurements with Leading Particles and Jets in pp collisions at $\sqrt{s} = 13$ TeV", The CMS Collaboration, CMS PAS FSQ-15-007, <https://cds.cern.ch/record/2104473>
- [5] "Measurement of the underlying event activity in inclusive Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV", The CMS Collaboration, JHEP 07 (2018) 032
- [6] "Double parton scattering, diffraction and effective cross section", D. Treleani, Phys.Rev.D76:076006,2007
- [7] "Study of double parton scattering using W + 2-jet events in proton-proton collisions at $\sqrt{s} = 7$ TeV", The CMS Collaboration, J. High Energ. Phys. (2014) 2014: 32
- [8] "Study of double parton scattering in photon + 3 jets final state in proton-proton collisions at 7 TeV", The CMS Collaboration, CMS PAS FSQ-12-017, <https://cds.cern.ch/record/2007815>
- [9] "Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV", The CMS Collaboration, J. High Energ. Phys. (2014) 2014: 94
- [10] "Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV" The CMS Collaboration, J. High Energ. Phys. (2018) 2018: 32
- [11] "Measurement of double parton scattering in same-sign WW production in p-p collisions at $\sqrt{s} = 13$ TeV with the CMS experiment" The CMS Collaboration. CMS PAS FSQ-16-009, <https://cds.cern.ch/record/2257583>