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CMS Forward and Small-x QCD Physics Results

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Abstract

An overview of the forward and small-x QCD physics programme at CMS is given. It covers the measurement of the leading charged particle and leading jet cross sections, soft diffractive cross section, dijet production with a large rapidity gap, exclusive WW production and constraints on Anomalous Quartic Gauge Couplings. Studies of double parton scattering using events with at least four jets, two of them initiated by b-quarks, and events with photon+3 jets are discussed as well.

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CMS Forward and Small-x QCD Physics Results *

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Abstract

An overview of the forward and small-x QCD physics programme at CMS is given. It covers the measurement of the soft diffractive cross section, dijet production with a large rapidity gap, exclusive WW production and constraints on Anomalous Quartic Gauge Couplings and the production of leading jets at small transverse momenta. Studies of double parton scattering using events with at least four jets, two of them initiated by b-quarks, and using events with photon+3 jets are discussed as well.

Keywords: QCD, small-x, forward physics, diffraction, BFKL, DGLAP, DPS, AQGC

1. Measurement of diffractive dissociation cross sections.

Measurements of diffractive dissociation cross sections in pp collisions at $\sqrt{s} = 7$ TeV are presented in kinematic regions defined by the masses M_X and M_Y of the two final-state hadronic systems separated by the largest rapidity gap in the event [1]. Differential cross sections are measured as a function of $\xi_X = M_X^2/s$ in the region $-5.5 < \log_{10}\xi_X < -2.5$, for $\log_{10}M_Y < 0.5$, dominated by single dissociation (SD), shown in Fig. 1 (top), and $0.5 < \log_{10}M_Y < 1.1$, dominated by double dissociation (DD), Fig. 1 (bottom), where M_X and M_Y are given in GeV. The measured cross sections compared to the PYTHIA 8 [2] tune 4C [3], PYTHIA 6 [4] tune Z2* [5] and PYTHIA 8 MBR [6] predictions. The predictions of PYTHIA 8 MBR are shown for two values of the ϵ parameter of the Pomeron trajectory.

The data are also analyzed in terms of the widest pseudorapidity gap adjacent to the edge of the CMS detector. In each event, particles are first ordered in η ,

Figure 1: Cross sections $d\sigma/d\log_{10}\xi_X$ for $\log_{10}M_Y < 0.5$ (top) and $0.5 < \log_{10}M_Y < 1.1$ (bottom) compared to predictions of various PYTHIA versions.

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and the largest pseudorapidity gap, $\Delta\eta^F$, is determined as $\Delta\eta^F = \max(|\eta_{\min} - \eta^-|, |\eta_{\min} - \eta^+|)$, where $\eta^\pm = \pm 4.7$ are the detector edges in η , and $\eta_{\max}(\eta_{\min})$ is the highest (lowest) η of the particle flow objects in the event.

Figure 2 shows the differential cross section $d\sigma/d\Delta\eta^F$ for events with at least one particle with $p_T > 200$ MeV in the region $|\eta| < 4.7$ compared to the corresponding predictions of PYTHIA 8 MBR ($\epsilon = 0.08$). The MC

Figure 2: Differential cross section $d\sigma/d\Delta\eta^F$ compared to the corresponding predictions of PYTHIA 8 MBR ($\epsilon = 0.08$).

predictions show that in the pseudorapidity range covered by the measurement, $|\eta| < 4.7$, a large fraction of nondiffractive events can be suppressed by means of the $\Delta\eta^F > 3$ requirement.

2. Dijet production with a large rapidity gap between the jets

Events with no particles produced between two leading jets have been studied in pp collisions at $\sqrt{s} = 7$ TeV, for jets with $p_T > 40$ GeV and $1.5 < |\eta| < 4.5$, reconstructed in opposite hemispheres of the CMS detector [7].

Figure 3 presents the dependence of the fraction of dijet events produced through colour singlet exchange (CSE), f_{CSE} , on the transverse momentum of the second-leading jet, $p_T^{\text{jet}2}$, compared to the results of the D0 [8] and CDF [9] collaborations obtained in similar analyses at $\sqrt{s} = 1.8$ TeV. At both energies the f_{CSE}

fraction exhibits a modest increase with $p_T^{\text{jet}2}$. In addition, a suppression of the gap fraction with increasing $\sqrt{s}$ is observed.

Figure 3: The fraction f_{CSE} as a function of $p_T^{\text{jet}2}$ as measured by CMS at $\sqrt{s} = 7$ TeV, and by D0 [8] and CDF [9] at $\sqrt{s} = 1.8$ TeV.

The study of CSE events as a function of the rapidity gap width may allow to disentangle the BFKL [10–12] dynamics from the DGLAP [13–15] evolution; the study is also sensitive to the contribution from rescattering processes, which can destroy the parton-level rapidity gap [16].

Figure 4 shows the dependence of f_{CSE} on $\Delta\eta_{jj}$ for $100 < p_T^{\text{jet}2} < 200$ GeV. The gap fraction increases with $\Delta\eta_{jj}$. Figure 4 also shows the comparison of the data with the prediction of the Mueller and Tang [17] model (MT) which is based on simplified BFKL calculations containing only the leading-log (LL) terms. The MT model does not reproduce the growth of f_{CSE} with $\Delta\eta_{jj}$, and underestimates the measured gap fractions.

3. Exclusive WW production and limits on AQGC

A search for exclusive or quasi-exclusive $\gamma\gamma \rightarrow W^+W^-$ production, $pp \rightarrow p^{(*)} + (1^+1^-, W^+W^-) + p^{(*)}$ at $\sqrt{s} = 8$ TeV is reported using data corresponding to an integrated luminosity of 19.7 fb^{-1} [18]. Events are selected by requiring the presence of an electron-muon pair with large transverse momentum $p_T(\mu^\pm e^\mp) > 30$ GeV (Fig. 5) and no associated charged particles detected from the same vertex. In the signal region 13 events are observed over an expected background of 3.5 ± 0.5 events, corresponding to an excess of 3.6σ over the background-only hypothesis. The observed yields and kinematic distributions are compatible with

Figure 4: The fraction f_{CSE} as a function of $\Delta\eta_{jj}$ measured in the $100 < p_T^{\text{jet2}} < 200$ GeV bin.

Figure 5: Muon-electron transverse momentum for events with zero associated tracks

the Standard Model prediction for exclusive and quasi-exclusive $\gamma\gamma \rightarrow W^+W^-$ production.

The dilepton transverse momentum spectrum is studied for deviations from the Standard Model, and the resulting upper limits are compared to predictions assuming anomalous quartic gauge couplings [19, 20]. Fig. 6 shows the excluded values of the anomalous coupling parameters a_0^W/Λ^2 and a_C^W/Λ^2 with $\Lambda_{\text{cutoff}} = 500$ GeV. The area outside the solid contour is excluded by this measurement at 95% CL.

Figure 6: excluded values of the anomalous coupling parameters a_0^W/Λ^2 and a_C^W/Λ^2 with $\Lambda_{\text{cutoff}} = 500$ GeV

4. Production of leading charged-particle jet

Most of the final-state hadrons produced in pp collisions at the LHC come from the hadronisation of quarks and gluons scattered in semi-hard interactions with exchanged momenta of $O(1 - 3)$ GeV. At such low values of p_T , the theoretical partonic cross section, $d\sigma/dp_T^2 \propto \alpha_S^2(p_T)/p_T^4$, becomes very large, and the integrated cross section $\sigma(p_T^{\text{min}}) = \int_{p_T^{\text{min}}} dp_T^2 d\sigma/dp_T^2$ exceeds even the total one.

Contrary to the inclusive particle or jet production cross sections, the *leading* particle or *leading* jet production cross sections must indeed approach the total inelastic cross section because only one particle or one jet, the one with highest p_T in this case, is considered per event.

Reference [21] proposes that the jet cross section integrated over $p_T > p_T^{\text{min}}$ can be used as a probe of the transition from the perturbative ($p_T^{\text{min}} \gg \Lambda_{\text{QCD}}$) to the non-perturbative region ($p_T^{\text{min}} \rightarrow \Lambda_{\text{QCD}}$), which should also be visible for cross sections defined in restricted ranges of pseudorapidity.

The results presented here are based on measurements of jets reconstructed from charged particles alone [22]. The yields, $r(p_T^{\text{min}})$, for pp collisions with a leading jet are measured as a function of a minimum transverse momentum, p_T^{min} :

$$r(p_T^{\text{min}}) = \frac{1}{N_{\text{evt}}} \int_{p_T^{\text{min}}} dp_T^{\text{lead}} \left(\frac{dN}{dp_T^{\text{lead}}} \right),$$

where N_{evt} is the number of selected events with a leading charged particle with $p_T > 0.4$ GeV and $|\eta| < 2.4$,

and N is the number of events with a leading jet with transverse momentum p_T^{lead} within $|\eta| < 1.9$.

Figure 7 shows the integrated distributions for the leading jet events for $p_T^{\text{min}} > 1$ GeV. The turnover

Figure 7: The integrated yield, $r(p_T^{\text{min}})$, of events with a leading jet within $|\eta| < 1.9$, as a function of p_T^{min} . The data are compared to various event generators. The predictions are scaled to the measured value of $r(p_T^{\text{lead}} > 14.3 \text{ GeV})$.

from a relatively flat to a steeply-falling distribution takes place between 1 and 10 GeV. The leading jet data are compared with PYTHIA 8 [2] with tunes 4C [3], CUET [23], and MONASH [24], HERWIG++ (version 2.7.0) [25] with tune UE-EE-5C [26], EPOS (version 1.99) [27, 28] with LHC tune, and QGSJETII-04 [29]. The leading charged particle and leading jet cross sections are best described by EPOS.

5. Studies of 2 light + 2 b jet production

Measurements of differential cross sections for the production of at least four jets, two of them initiated by a b-quark, in proton-proton collisions are presented as a function of the transverse momentum p_T and pseudorapidity η , together with the correlations in azimuthal angle and the p_T -balance among the jets [30]. The data sample was collected in 2010 at a center-of-mass energy of 7 TeV with the CMS detector at the LHC with an integrated luminosity of 3 pb^{-1} . Events with at least four

jets with $p_T > 20 \text{ GeV}$ are selected; two of them are the highest transverse momentum (leading) jets classified as originated by b-quarks, while the other two are the remaining highest p_T jets, regardless of their flavour. To study the production of pairs of different flavoured jets via double parton scattering (DPS) the former two jets are associated in the “b-quark jet pair” (bottom), while the latter two ones compose the “light-quark jet pair” (light).

Figure 8 shows the differential normalized cross sections as a function of the azimuthal angle ΔS between the two dijet pairs, defined as:

$$\Delta S = \arccos \left(\frac{\vec{p}_T(\text{bottom}_1, \text{bottom}_2) \cdot \vec{p}_T(\text{light}_1, \text{light}_2)}{|\vec{p}_T(\text{bottom}_1, \text{bottom}_2)| \cdot |\vec{p}_T(\text{light}_1, \text{light}_2)|} \right).$$

This distribution is found to be the most DPS-sensitive observable. The measured distribution is compared to predictions of POWHEG+PYTHIA 8 [31, 32], MADGRAPH+PYTHIA 8 [33], PYTHIA 6 [4], PYTHIA 8 [2] and HERWIG ++ [25]. ΔS is not well described by any prediction: in particular, all of them, except HERWIG ++ and PYTHIA 8 in a lesser extent, underestimate the region at values of $\Delta S < 2$, and do not well follow the decreasing shape towards lower values. This study shows the need for multiple parton interaction (MPI) contributions in the simulation in order to describe correlation observables between jets.

Figure 8: Normalized cross sections as a function of ΔS , compared to predictions of POWHEG+PYTHIA 8, MADGRAPH+PYTHIA 8, PYTHIA 6, PYTHIA 8 and HERWIG++.

6. Studies of $\gamma + 3$ jet production

Distributions sensitive to double parton scattering are investigated in the photon + 3 jets final state in proton-proton collisions at a center-of-mass energy of 7 TeV [34]. The data were collected by the CMS experiment at the LHC with an integrated luminosity of 36 pb^{-1} in 2010. Events with one photon and at least three jets are analyzed by investigating the azimuthal angular differences for the di-jet pair and the balance in transverse momentum of the photon-jet and di-jets pairs. The measurement requires the transverse momentum $p_T > 75 \text{ GeV}$ for the leading (highest p_T) photon and the leading jet and $p_T > 20 \text{ GeV}$ for the other jets.

The photon source of DPS signal events can be direct photons and fragmentation photons. Events containing photon + 3 jets produced from single parton scattering or misidentified photon + 3 jets caused by decays of π^0 and η mesons constitute an irreducible background.

Fig. 9 shows the normalized differential cross section as a function of the azimuthal angle between the p_T vectors of the photon-jet pair and the di-jet pair,

$$\Delta S = \Delta\varphi(\vec{p}_T(\gamma, \text{jet1}), \vec{p}_T(\text{jet2}, \text{jet3})),$$

where γ , jet1, jet2, and jet3 stand for the leading photon, the leading jet, the second leading jet, and the third leading jet, respectively. The predictions of PYTHIA 8 [2], MADGRAPH + PYTHIA 8 [33] and SHERPA [35] are compatible with the measured distribution. Switching off the MPI simulation for MADGRAPH + PYTHIA and SHERPA causes about 5–10% differences. The reason the MPI causes only small changes in ΔS is due to various background components which reduce the possible sensitivity for the DPS signal contribution.

References

- [1] CMS Collaboration, Phys. Rev. D 92, 012003 (2015).
- [2] T. Sjöstrand, S. Mrenna and P. Skands, Comput. 573 Phys. Commun. 178 (2008) 852.
- [3] R. Corke and T. Sjöstrand, JHEP 03 259 (2011) 032.
- [4] T. Sjöstrand, S. Mrenna and P. Skands, JHEP 05 571 (2006) 026.
- [5] CMS Collaboration, JHEP 04 (2013) 072.
- [6] R. Ciesielski and K. Goulianos, 36th Int. Conf. on High Energy Physics (ICHEP2012), A. Limosani, ed., p. 301. 2013.
- [7] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-FSQ-12-001, 2015.
- [8] D0 Collaboration, Phys. Lett. B440 (1998) 189.
- [9] CDF Collaboration, Phys. Rev. Lett. 80 (1998) 1156.
- [10] E. E. Kuraev, L. N. Lipatov, and V. S. Fadin Sov. Phys. JETP 45 (1977) 199.
- [11] Y. Y. Balitsky and L. N. Lipatov Sov. J. Nucl. Phys. 28 (1978) 822.
- [12] L. N. Lipatov Sov. Phys. JETP 63 (1986) 904.

Figure 9: Normalized differential cross sections as a function of ΔS compared to different MC predictions.

- [13] V. N. Gribov and L. N. Lipatov Sov. J. Nucl. Phys. 15 (1972) 438.
- [14] G. Altarelli and G. Parisi Nucl. Phys. B126 (1977) 298.
- [15] Y. L. Dokshitzer Sov. Phys. JETP 46 (1977) 641.
- [16] O. Kepka, C. Marquet, and C. Royon, Phys.Rev. D83 (2011) 034036.
- [17] A. H. Mueller and W.-K. Tang, Phys. Lett. B284 (1992) 123.
- [18] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-FSQ-13-008, 2015.
- [19] T. Pierzchala and K. Piotrkowski, Nucl.Phys.Proc.Suppl. 179-180 (2008) 257264.
- [20] E. Chapon, C. Royon, and O. Kepka, Phys.Rev. D81 (2010) 074003.
- [21] A. Grebenyuk et al., Phys. Rev. D 86 (2012) 117501.
- [22] CMS Collaboration, arXiv:1507.00233.
- [23] CMS Collaboration, PoS DIS2014 (2014) 100.
- [24] P. Skands, S. Carrazza, and J. Rojo, Eur. Phys. J. C 74 (2014) 3024.
- [25] M. Bahr et al., Eur. Phys. J. C 58 (2008) 639.
- [26] J. Bellm et al., arXiv:1310.6877.
- [27] K. Werner, F.-M. Liu, and T. Pierog, Phys. Rev. C 74 (2006).
- [28] T. Pierog et al., arXiv:1306.0121.
- [29] S. Ostapchenko, Phys. Rev. D 83 (2011) 014018.
- [30] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-FSQ-13-010, 2015.
- [31] P. Nason, JHEP 0411 (2004) 040,
- [32] S. Frixione, P. Nason, and C. Oleari, JHEP 0711 (2007) 070.
- [33] J. Alwall et al., JHEP 1106 (2011) 128.
- [34] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-FSQ-12-017, 2015.
- [35] T. Gleisberg et al., JHEP 02 (2009) 007.