PROCEEDINGS OF SCIENCE

Central exclusive and diffractive physics measurements at CMS and TOTEM

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Diffractive processes are important non-perturbative phenomena of strong interaction, which are studied in various measurements at the LHC. Recent results of the CMS and TOTEM experiments are presented in this paper. First, the measurement of central exclusive and semiexclusive $\pi^+\pi^-$ production at 5.02 and 13 TeV is discussed. The total and differential cross sections of final states with $p_T(\pi) > 0.2$ GeV, $|\eta(\pi)| < 2.4$ are measured. In the second part of the paper, the measurement of the total and differential cross sections as functions of four-momentum transfer squared t and proton fractional momentum loss ξ, in the $0.03 < |t| < 1.0$ GeV^2 and $0 < \xi < 0.1$ kinematic region, with at least two jets with $p_T > 40$ GeV and $|\eta| < 4.4$ is presented. This latter measurement utilized the proton tagging capabilities of the Roman Pot detectors of the TOTEM experiment.

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1. Introduction

Diffractive and exclusive processes are one of the most actively researched topics of the physics of the strong interaction. This paper presents two recent measurements from the CMS Collaboration: the study of central exclusive and semiexclusive dipion production at $\sqrt{s}$ = 5.02 and 13 TeV [1], and the measurement of single diffractive dijet production, using proton tagging at $\sqrt{s}$ = 8 TeV [2].

2. Central exclusive and semiexclusive dipion production at 5.02 and 13 TeV

In central exclusive processes, the two protons remain intact and a central system is produced via particle exchange. The graphs of the two dominant processes at LHC collision energies, the double pomeron exchange (DPE) and the vector meson photoproduction (VMP), are shown in Fig. 1. The quantum numbers of the exchanged particles restrict the quantum numbers of the possible final states, thus exclusive processes act as quantum number filter, providing a unique opportunity to study certain low mass resonances.

The total and differential cross sections of central exclusive and semiexclusive $\pi^+\pi^-$ production was measured by the CMS Collaboration. The study was performed using proton-proton collision data at $\sqrt{s}$ = 5.02 and 13 TeV, corresponding to 522 and 258 μb^{-1} integrated luminosities, respectively. Exclusive candidate events are selected by requiring exactly two, oppositely charged tracks, and no activity in the calorimeters, except the 3σ region around the extrapolated impact points of the tracks on the calorimeter surfaces. The pions were identified based on their specific ionization energy loss. The efficiency of the tracking was ensured by studying final states with $p_T(\pi) > 0.2$ GeV, $|\eta(\pi)| < 2.4$. Since the scattered protons are not detected in this measurement, therefore protons may dissociate into low mass forward states, beyond the pseudorapidity coverage of the CMS hadron forward calorimeters. This is the so-called semiexclusive production, which were also included in this measurement with dissociation products in the $|\eta| > 4.9$ region.

The measured total cross section of central exclusive and semiexclusive $\pi^+\pi^-$ production, with final states of $p_T(\pi) > 0.2$ GeV, $|\eta(\pi)| < 2.4$ and proton dissociation products at $|\eta| > 4.9$ is:

$$\sigma(\sqrt{s} = 5.02 \text{ TeV}) = 32.6 \pm 0.7(\text{stat}) \pm 6.0(\text{syst}) \pm 0.08(\text{lumi})\ \mu\text{b}, \quad (1)$$

$$\sigma(\sqrt{s} = 13 \text{ TeV}) = 33.7 \pm 1.0(\text{stat}) \pm 6.2(\text{syst}) \pm 0.08(\text{lumi})\ \mu\text{b}. \quad (2)$$

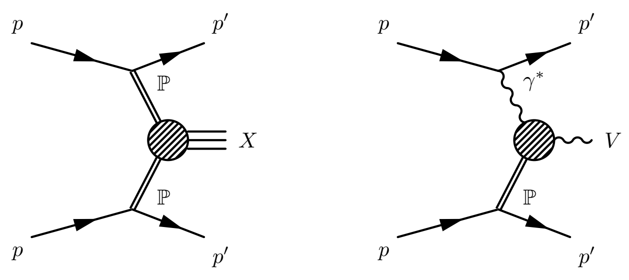

Figure 1: Two dominant processes of central exclusive production at LHC collision energies: double pomeron exchange (left) and vector meson photoproduction (right).

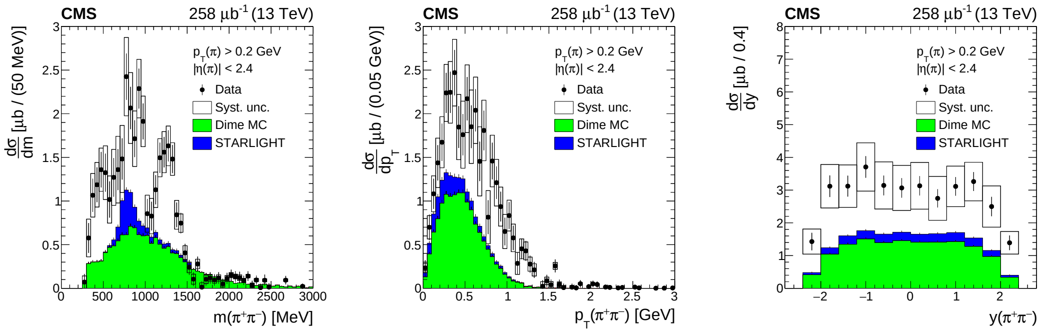

Figure 2: The differential cross sections of central exclusive and semiexclusive $\pi^+\pi^-$ production, with final states of $p_\mathrm{T}(\pi) > 0.2$ GeV, $|\eta(\pi)| < 2.4$ and proton dissociation products at $|\eta| > 4.9$ as functions of invariant mass, transverse momentum and rapidity of pion pair at 13 TeV [1].

The differential cross sections as functions of invariant mass, transverse momentum and rapidity of the pion pair at 13 TeV are shown in Fig. 2. The distributions are similar for the 5.02 TeV dataset. The results are compared to the Monte Carlo simulation predictions of the Starlight generator, that models the exclusive $\rho(770)$ photoproduction [4], and the Dime MC generator, modeling the non-resonant DPE contribution [3]. At the time, when this measurement was performed, there was no simulation available to describe the scalar and tensor low mass resonances. An excess of events is measured with respect to Dime MC in the invariant mass region below 600 MeV, which suggests the presence of the very wide $\mathrm{f}_0(500)$ resonance. As expected from Starlight, there is an enhancement around 7-800 MeV, corresponding to the $\rho^0(770)$ vector meson. A sharp drop is observed at around 1 GeV, which effect was already seen in previous measurements [5] and explained by the interference between the $f_0(980)$ scalar resonance and the non-resonant contribution. A significant bump is present around 1250–1300 MeV, the $f_2(1270)$ tensor resonance. Finally the mass spectra were fitted by the sum of a non-resonant contribution and four interfering Breit-Wigner resonances, modelling $\mathrm{f}_0(500)$, $\rho^0(770)$, $\mathrm{f}_0(980)$, and $\mathrm{f}_2(1270)$. The fit results are shown in Fig. 3.

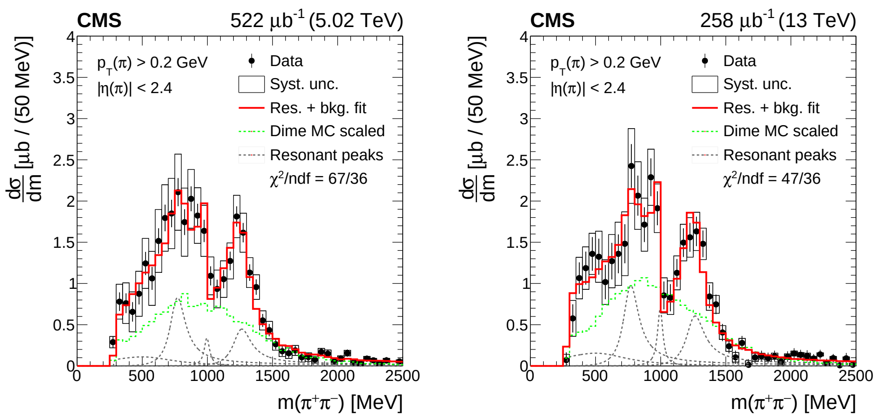

Figure 3: The fit of mass spectra by the sum of a non-resonant (modeled by Dime MC) and four interfering Breit-Wigner resonances ($\mathrm{f}_0(500)$, $\rho^0(770)$, $\mathrm{f}_0(980)$ and $\mathrm{f}_2(1270)$) [1].

3. Single diffractive dijets with proton tagging at 8 TeV

Dijets can be produced in single diffractive collisions, as illustrated in Fig. 4. According to the factorization theorem these hard diffractive processess can be described by a convolution of diffractive parton distribution functions and hard scattering cross sections calculated from pQCD. This method was used previously to successfully describe diffraction in electron-proton collisions, however in hadron-hadron collisions the factorization theorem is spoiled by the soft rescattering between the spectator partons.

Experimentally single diffractive dijet events are characterized by a large rapidity gap around the proton. Alternatively, these events can be selected by detecting the scattered protons by the Roman Pot (RP) detectors of the TOTEM experiment [6], which are small tracking detectors, located at ±147 and ±220 m from the interaction point. The latter method gives a direct measurement of the t squared four-momentum transfer. The fractional momentum loss can be measured in two ways:

$$\xi_{\mathrm{TOTEM}} = 1 - \left|\frac{\mathbf{p}_f}{\mathbf{p}_i}\right|, \tag{3}$$

$$\xi^{\pm}_{\mathrm{CMS}} = \frac{\sum_i (E^i \pm p^i_z)}{\sqrt{s}}, \tag{4}$$

where the first is a direct measurement using the RPs, and in the second equation, the sum is going over all reconstructed particles, where E^i is the energy and p^i_z is the longitudinal momentum component of them. Since CMS has a limited pseudorapidity coverage, generally $\xi_{\mathrm{CMS}} - \xi_{\mathrm{TOTEM}} \leq 0$.

The measurement was performed using pp collisions with 8 TeV center-of-mass energy and low probability of overlapping pp interactions in the same bunch crossing, and special beam optics setup with $\beta^* = 90$ m. The collected data corresponds to 37.5 nb^{-1} integrated luminosity. First, dijet events were selected at the trigger level requiring at least two jets with $p_{\mathrm{T}} > 20$ GeV. At the offline level, at least two jets were required with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 4.4$. Furthermore at least one reconstructed primary vertex and at least one proton detected by the RPs is required. Elastic scattering events are rejected, when two protons are observed in the opposite side RPs with the same horizontal and vertical scattering angle within detector resolution. To suppress contributions from beam halo and pileup events, the above-mentioned $\xi_{\mathrm{CMS}} - \xi_{\mathrm{TOTEM}} \leq 0$ condition is also imposed. The results were studied in the phase space of $0.03 < |t| < 1.0$ GeV^2 and $0 < \xi_{\mathrm{TOTEM}} < 0.1$.

The diffractive dijet production was simulated by Pythia 8 [8] with the Dynamic Gap model, the 4C, and the CUETP8M1 tunes and also by Pomwig [7], which includes Reggeon exchanges and

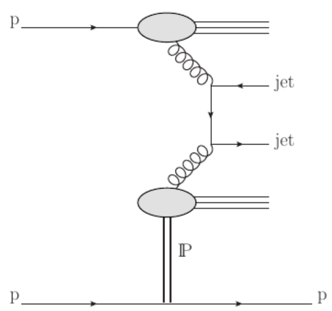

Figure 4: Production of dijets in a single diffractive collision.

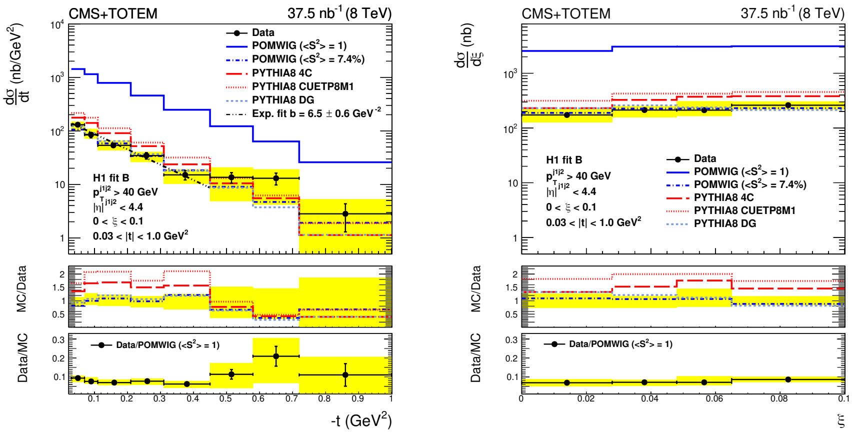

Figure 5: The differential cross sections of single-diffractive dijet production as a function of transferred four-momentum and fractional momentum loss [2].

uses a constant survival factor. Non-diffractive dijet events were simulated using Pythia 6 with the Z2 tune and Pythia 8 with the 4C, the CUETP8M1, and the CUETP8S1 tunes. In these simulation, beam protons are transported to the RPs. The CMS detector response to these events are simulated by Geant4, whereas the acceptance and resolution of RPs are parametrised as a function of proton kinematics.

The cross section of the single-diffractive dijet production is measured in the $0.03 < |t| < 1.0\ \mathrm{GeV}^2$ and $0 < \xi_{\mathrm{TOTEM}} < 0.1$ kinematic region:

$$\sigma_{\mathrm{jj}}^{\mathrm{pX}} = 21.7 \pm 0.9\ (\mathrm{stat})^{+3.0}_{-3.3}\ (\mathrm{syst}) \pm 0.9\ (\mathrm{lumi})\ \mathrm{nb}. \tag{5}$$

Moreover, the cross sections as a function of t and ξ are also studied, as shown in Fig. 5. Pythia 8 with the DG model and Pomwig gives good description, whereas Pythia 8 with the 4C and the CUETP8M1 tunes predicts higher contribution.

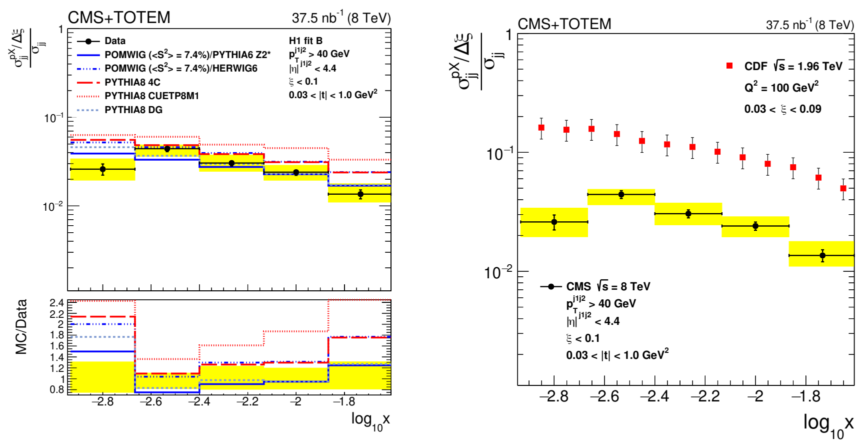

Figure 6: Ratio of single-diffractive and inclusive dijet production cross sections compared to simulation (left) and CDF results (right) [2].

The ratio of single-diffractive and inclusive dijet production cross sections is shown in Fig. 6. Though POMWIG and PYTHIA 8 with the DG model gives better description, there is a large deviation from all models at low-x. The cross section ratios decreased compared to CDF results [9], which feature was already seen in CDF, and can be explained by the increasing probability of soft rescattering.

4. Conclusions

The measurements of exclusive and diffractive processes provide opportunity to study non-perturbative phenomena in QCD, such as low mass resonances and soft rescattering. The exclusive and semiexclusive total and differential cross sections of pion pair production were measure in pp collisions with 5.02 and 13 TeV collision energy. The measured invariant mass spectra were fitted by a sum of four interfering Breit-Wigner resonances and a non-resonant contribution. Single-diffractive dijet production also studied in 8 TeV pp collisions. It is found that PYTHIA 8 with the DG model and POMWIG with a constant survival factor gives a good description of data. A decrease in the cross section with respect to CDF measurement is observed, which is explained by the increased probability of soft rescattering at 8 TeV.

Acknowledgments

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