The Compact Muon Solenoid Experiment
Conference Report

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

04 December 2015 (v4, 15 February 2016)

Review of Diffraction at the LHC

Robert Ciesielski for the "QCD, Electroweak, Exotica (SUSY, ...), heavy ions", "Standard Model, QCD, W,Z,DIFF,FW", ATLAS, CMS and LHCb collaborations.

Abstract

We present the review of the recent results on diffraction from the LHC.

Presented at *EDSBlois2015 The 16th conference on Elastic and Diffractive Scattering*

REVIEW OF DIFFRACTION AT THE LHC*

ROBERT CIESIELSKI

The Rockefeller University 1230 York Avenue, New York, NY 10065, USA

on behalf of the ALICE, ATLAS, LHCb, CMS and TOTEM Collaborations

We present the review of the recent results on diffraction from the LHC.

PACS numbers: 12.38.QK,13.85.-t,13.85.Dz,13.85.Lg

1. Introduction

In hadron-hadron scattering a substantial fraction of the total cross section can be attributed to diffractive interactions, characterized by the presence of at least one non-exponentially suppressed large rapidity gap (LRG), i.e. a region of pseudorapidity η devoid of particles. The LRG is associated with a color-singlet exchange carrying the vacuum quantum numbers, commonly referred to as *pomeron* exchange. Diffractive processes are classified as soft or hard, depending on the presence of a hard scale in the interaction.

Soft diffractive cross sections cannot be calculated within perturbative Quantum Chromodynamics (pQCD), and are commonly described by phenomenological models. Predictions of these models generally differ when extrapolated from Tevatron center-of-mass energies to LHC. Therefore, measurements of diffractive cross sections at the LHC provide a valuable input for understanding diffraction and improving its theoretical description. Together with the total and elastic cross section results, are crucial for the proper modeling of the full final state of hadronic interactions in event generators, and the simulation of hadronic showers in cosmic ray physics.

Hard diffraction events are especially interesting because they can be studied in terms of pQCD, thus providing an opportunity to investigate the nature of the *pomeron* in terms of quarks and gluons, and to establish a link between soft and hard regimes. Exclusive production of simple identified final states reveals an interesting connection between diffraction and the physics of heavy-ion collisions through the concept of saturation in the regime of high parton densities; and also offers the possibility for searches for beyond-Standard-Model phenomena or exotic particles, such as glueballs.

* Presented at the EDS-Blois 2015 Conference, Borgo, Corsica, France

2. Total and elastic cross sections

TOTEM measured the total σ_{tot} , elastic σ_{el} and total inelastic, $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$, hadronic pp cross sections at $\sqrt{s} = 7$ and 8 TeV, using data from special runs with the $\beta^* = 90$ m beam optics [1, 2, 3, 4]. Elastic cross sections were obtained from the integrated and extrapolated differential $d\sigma/d|t|$ cross section, where $|t|$ is the four-momentum transfer squared at the proton vertex, in the region $0.005 < |t| < 2.5$ GeV², with protons tagged in the TOTEM Roman Pot detectors located at $z = \pm 220$ m downstream of the CMS detector. The total pp cross section was obtained from the elastic scattering using the optical theorem. At 7 TeV, $\sigma_{el} = 25.4 \pm 1.1$ mb, $\sigma_{tot} = 98.6 \pm 2.2$ mb and $\sigma_{inel} = 73.2 \pm 1.6$ mb were measured by TOTEM (luminosity dependent method [1]), in agreement with the results of a similar measurement by ATLAS [5], $\sigma_{el} = 24.00 \pm 0.19$ (stat) ± 0.57 (syst) mb, $\sigma_{tot} = 95.35 \pm 0.38$ (stat) ± 1.25 (exp) ± 0.37 (extr) mb, and $\sigma_{inel} = 71.34 \pm 0.36$ (stat) ± 0.83 (syst) mb, based on data with protons tagged in the ALFA detectors ($z = \pm 240$ m). These results were found to have a big impact on the phenomenological model predictions. An interesting summary of the evaluation of the predictions before and after including the LHC data can be found in Ref. [6].

TOTEM also measured elastic scattering at $\sqrt{s} = 8$ TeV using a high-statistics data sample [7]. With an unprecedented precision below 1%, an evidence for a non-exponential differential cross-section was observed, and a purely exponential dependence was excluded with a significance greater than 7 standard deviations. Two extended parameterizations, with quadratic and cubic polynomials in the exponent, were found to be well compatible with the data. Another study was based on the data taken with the $\beta^* = 1000$ m optics, which allowed to reach $|t|$ values as low as $|t| \simeq 6 \times 10^{-4}$ GeV², and to observe the effects of Coulomb-nuclear interference [8]. A study of the phase of the hadronic amplitude is ongoing.

3. Soft diffractive cross sections

ATLAS has measured [9] the inclusive cross section as a function of the forward pseudorapidity gap, $\Delta\eta^F$, defined as the distance of the most-forward-detected particle to the edge of the central detector [10] ($|\eta| = 4.9$). The differential $d\sigma/d\Delta\eta^F$ cross section at $\sqrt{s} = 7$ TeV (Fig. 1, left) in the region $\Delta\eta^F > 3$ is dominated by the diffractive events, with an approximately equal contribution from the single-dissociation (SD, $pp \rightarrow Xp$ or $pp \rightarrow Yp$) and double-dissociation (DD, $pp \rightarrow XY$) diffraction processes, in which a low-mass dissociated system X or Y escapes undetected.

CMS has measured [11] the SD and DD cross sections at $\sqrt{s} = 7$ TeV, using the events with a forward or central pseudorapidity gap in the

Fig. 1. Left: Differential cross section as a function of the forward rapidity gap, $\Delta\eta^F$, measured by ATLAS [9], compared to the PYTHIA8 MC simulation. Right: Cross section $d\sigma/d\log_{10} \xi_X$ measured by CMS [11] for $\log_{10} M_Y < 0.5$ (SD dominated), compared to PYTHIA8-4C, PYTHIA8 MBR, and PYTHIA6-Z2* predictions.

detector [12] ($|\eta| < 4.7$). In the forward-gap sample ($\Delta\eta^F > 3$), sub-samples enhanced in SD and DD events were selected by requiring an absence or a presence of an energy deposit in the CASTOR calorimeter (located at $-6.6 < \eta < -5.2$, in the direction of the gap). This allowed to measure the differential cross sections as a function of $\xi_X = M_X^2/s$, in the range $-5.5 < \log_{10} \xi_X < -2.5$, for $\log_{10} M_Y < 0.5$ (dominated by SD), and $0.5 < \log_{10} M_Y < 1.1$ (dominated by DD), where M_X and M_Y correspond to diffractive masses (given in GeV). The cross sections were compared to MC predictions by PYTHIA8-4C, PYTHIA8-MBR and PYTHIA6-Z2* (Fig. 1 right, for the SD-dominated sample), and PHOJET, QGSJET-II 03, QGSJET-II 04, EPOS (not shown). The data are able to distinguish between different diffractive models, favoring PYTHIA8-MBR [13] simulation. Similar conclusions may be drawn from the comparison to the differential cross section measured as a function of the width of the central pseudorapidity gap $\Delta\eta$ for $\Delta\eta > 3$, $\log_{10} M_X > 1.1$, and $\log_{10} M_Y > 1.1$ (DD dominated). The SD and DD cross sections integrated over the above three regions were used to extract the total SD and DD cross sections of $\sigma^{\text{SD}} = 8.84 \pm 0.08(\text{stat})^{+1.49}_{-1.38}(\text{syst})^{+1.17}_{-0.37}(\text{extrap})$ mb and $\sigma^{\text{DD}} = 5.17 \pm 0.08(\text{stat})^{+0.55}_{-0.57}(\text{syst})^{+1.62}_{-0.51}(\text{extrap})$ mb in the regions of $\xi < 0.05$ and $\Delta\eta > 3$, respectively (after an extrapolation by a factor of ~ 2 with PYTHIA8-MBR).

The SD cross section at $\sqrt{s} = 7$ TeV has been also measured by TOTEM [8], based on events with one proton in the Roman Pot detectors and the activity in the TOTEM T1 ($3.1 < |\eta| < 4.7$) or T2 ($5.3 < |\eta| < 6.5$) telescopes. The differential $d\sigma/d|t|$ cross section was measured in three ranges of diffractive masses, M_X , selected by different configurations of active T1 and T2 detectors. The cross section integrated over the entire accessible mass range,

99 $3.4 < M_X < 1000$ GeV, was measured to be 6.5 ± 1.3 mb. TOTEM has
 100 also measured [14] the DD cross section of 120 ± 25 μb in the region of low
 101 diffractive masses $3.4 < M_X < 8$ GeV and $3.4 < M_Y < 8$ GeV detected in
 102 the T2 telescopes (and empty T1 detectors).

103

4. Hard diffraction

104 A striking feature of hard diffractive cross sections in hadron-hadron
 105 collisions is the observation of the pQCD factorization breaking, manifesting
 106 as a suppression of diffractive cross sections at the Tevatron, by an order of
 107 magnitude, relative to the predictions based on HERA diffractive PDFs, see
 108 e.g. [15]. This suppression, quantified by the so-called *rapidity gap survival*
 109 *probability*, is understood as due to additional soft multiparton interactions.

110 Obtaining results on hard diffraction at higher energies at the LHC has
 111 been hampered by a limited detector coverage of available rapidity space,
 112 which leads to difficulties in reconstructing large rapidity gaps and separat-
 113 ing hard diffractive events from nondiffractive. For example, in the CMS
 114 analysis of SD dijets at $\sqrt{s} = 7$ TeV with the central CMS detector [16],
 115 diffractive events were selected in a limited region of the diffractive variable ξ
 116 (fractional proton momentum loss), $0.0003 < \xi < 0.002$, and a rapidity gap
 117 survival probability of 0.12 ± 0.05 (LO) and 0.08 ± 0.04 (NLO) was extracted,
 118 sensitive to the contribution from non-diffractive and DD backgrounds. A
 119 similar ongoing analysis at $\sqrt{s} = 8$ TeV, using common 2012 CMS+TOTEM
 120 data and the additional requirement that the scattered proton be detected
 121 in the TOTEM Roman Pot, has demonstrated good control of the back-
 122 ground [17], and aims at measuring the cross section as a function of $|t|$ and
 123 other diffractive variables.

124 CMS has performed a study of events with a large rapidity gap in the
 125 η region between two jets at $\sqrt{s} = 7$ TeV [18]. The jet-gap-jet events
 126 were first observed by CDF [19] and D0 [20], and the topology has been
 127 suggested as being sensitive to effects of the BFKL dynamics [21]. The
 128 Tevatron data were successfully described by models based on the NLO
 129 BFKL evolution equations [22, 23], convoluted with the contribution from
 130 rescattering processes. Fig. 2 (left) shows the color-singlet-exchange (CSE)
 131 fractions, defined as a ratio of jet-gap-jet events to all dijet events, measured
 132 by CMS as a function of the second-leading jet p_T , compared to the results
 133 of CDF and D0. The data are a factor of two suppressed with respect to 1.8
 134 TeV data, indicating stronger contribution from soft rescattering processes
 135 at higher energy. A preliminary comparison to the predictions of Ref. [22]
 136 reveals that the modeling of rescattering processes, which worked well at
 137 Tevatron energies, needs additional adjustments to describe the 7 TeV data.

138 The joined CMS and TOTEM runs at $\sqrt{s} = 13$ TeV in 2015, based on
 139 a larger data sample, will allow more hard diffraction measurements to be

Fig. 2. Left: Color-singlet-exchange fractions measured by CMS [18] at $\sqrt{s} = 7$ TeV as a function of the second leading jet p_T , compared to the Tevatron results. Right: CMS [27] limits on anomalous quartic gauge couplings at $\sqrt{s} = 8$ TeV.

performed, to be further continued by the CT-PPS (collaboration between CMS and TOTEM on the Precision Proton Spectrometers) [24], and by the AFP (ATLAS Forward Physics) projects [25].

5. Exclusive processes

The central exclusive production in hadron-hadron collisions may proceed by photon-photon, pomeron-pomeron ($\mathbb{P}$ - $\mathbb{P}$), or photon-pomeron (γ - $\mathbb{P}$) interactions. The photon-photon exchange allows to test QED predictions and search for beyond-Standard-Model physics. The $\mathbb{P}$ - $\mathbb{P}$ exchange selects the $I^G(J^{PC}) = 0^+(\text{even})^{++}$ states and allows to study spectroscopy of isoscalar states (including glueballs). The γ - $\mathbb{P}$ exchange allows to study the $\gamma p \rightarrow Vp$ process (with $V = \rho, \phi, J/\psi, \Upsilon$), which exhibits a high sensitivity to the gluon distribution in the proton at very low Bjorken- x . At the LHC, it may be used to search for effects of gluon saturation.

ATLAS measured the cross section for the exclusive $\gamma\gamma \rightarrow l^+l^-$ production at $\sqrt{s} = 7$ TeV [26], for centrally produced high- p_T muons and electrons. The ratio of the cross sections, relative to the QED predictions, which have an uncertainty of about 2%, was measured to be 0.791 ± 0.041 (stat) ± 0.026 (syst) ± 0.013 (theor) for muons and 0.863 ± 0.070 (stat) ± 0.037 (syst) ± 0.015 (theor) for electrons, indicating a suppression due to soft rescattering effects. CMS measured the cross section for the exclusive $\gamma\gamma \rightarrow W^+W^-$ production at $\sqrt{s} = 8$ TeV [27], and set the world-stringest limits on anomalous quartic gauge couplings (Fig. 2, right), which are a factor of 20 (100) better than the Tevatron [28] (LEP [29]) limits.

The first measurement of the $\mathbb{P}$ - $\mathbb{P}$ induced production of $J/\psi + J/\psi$ and $J/\psi + \psi'$ pairs in pp collisions was performed by LHCb [30], who found

Fig. 3. Cross sections of exclusive vector-meson production measured as a function of $W_{\gamma p}$ for the (left) J/ψ meson by ALICE [32] and (right) Υ meson by LHCb [33].

165 57 $J/\psi + J/\psi$ and seven $J/\psi + \psi'$ candidates in events with four tracks and
 166 at least 3 muons. The cross section for the exclusive $J/\psi + J/\psi$ production
 167 was measured to be 24 ± 9 pb, in agreement with theoretical predictions.

168 LHCb also measured cross sections for the exclusive production of J/ψ
 169 and ψ' mesons at $\sqrt{s} = 7$ TeV [31], with dimuons at forward rapidities,
 170 $2 < y < 4.5$. The measured $d\sigma/dy$ cross sections favor NLO over LO QCD
 171 predictions, and agree with the models that include saturation effects. The
 172 J/ψ result was used to extract the cross section as a function of the photon-
 173 proton center-of-mass energy $W_{\gamma p}$. In the high- $W_{\gamma p}$ region ($400 < W_{\gamma p} <$
 174 1100) the data are well described by the function W^δ , $\delta = 0.67$, extracted
 175 from the fit to the HERA data ($30 < W_{\gamma p} < 300$). ALICE measured the
 176 exclusive J/ψ production cross section in p-Pb collisions (with the lead-ion
 177 serving as the source of the photon), for the J/ψ in rapidity $2.5 < y < 4$ [32].
 178 The cross section measured as a function of $W_{\gamma p}$ is compared to HERA
 179 results in Fig. 3 (left). The parameters of the power-law fit to ALICE
 180 results are consistent with those of HERA, indicating no change in gluon
 181 behavior at the LHC energies compared to HERA. LHCb also measured the
 182 exclusive Υ production cross section at $\sqrt{s} = 7$ and 8 TeV [33], as a function
 183 of dimuon rapidity and $W_{\gamma p}$. In Fig. 3 (right) the results are compared to the
 184 LO and NLO QCD predictions, favoring strongly the NLO calculations. For
 185 the future LHCb analyzes, the installation of HERSCHEL shower counters
 186 down to $\eta = \pm 9$ will greatly reduce the non-exclusive backgrounds.

187 The cross section of coherent J/ψ photoproduction was also measured
 188 in Pb-Pb collisions, in two rapidity intervals by ALICE [34, 35] and in one
 189 rapidity interval by CMS [36]. This process, with the lead-ion serving as
 190 both a source and a target, allows a study of nuclear gluon shadowing. The
 191 ALICE and CMS data agree with the models which include nuclear gluon
 192 shadowing employing the EPS09 parametrization. ALICE also measured
 193 photoproduction of ρ^0 in Pb-Pb collisions [37], which is well described by
 194 the STARLIGHT simulation using the Glauber model.

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