7.4. Diffraction and forward physics

7.4.1. Introduction

This section outlines the diffractive and forward physics that CMS can do – together with the TOTEM experiment. The CMS and TOTEM detectors involved are presented in Chapter 7 of Volume 1 of the CMS Physics TDR [7].

The combined phase space coverage of the two experiments makes it possible to study many physics subjects in diffractive interactions – from QCD and the investigation of the low-x structure of the proton to the production of SM and MSSM Higgs bosons. Diffractive events are characterised by the fact that the incoming proton(s) emerge from the interaction intact, or excited into a low mass state, with only a small energy loss. Diffractive processes with proton energy losses up to a few per cent are dominated by the exchange of an object with vacuum quantum numbers, the so called Pomeron, now understood in terms of partons from the proton. For larger energy losses, mesonic exchanges – Reggeons and pions – become important. The topology of diffractive events is characterised by a gap in the rapidity distribution of final-state hadrons due to the lack of colour of the exchanged object.

Events with a fast proton in the final state can also originate from the exchange of a photon. In particular, forward tagging one leading proton allows the selection of photon-proton events with known photon energy; likewise, tagging two leading protons gives access to photon-photon interactions of well known centre-of-mass energy.

Triggering of diffractive/forward events is discussed in [247] and in Appendix E.3. More details on the work presented here can be found in [248].

7.4.2. The interest of diffractive interactions

The study of hard diffraction has been pioneered by the UA8 experiment at CERN [249]. There have been major advances in this field recently, largely driven by the study of diffraction at HERA and the Tevatron. The essential results are discussed in [250] and can be summarised as follows:

- Many aspects of hard diffractive processes are well understood in QCD: the presence of a hard scale allows the use of perturbative techniques and thus to formulate the dynamics in terms of quarks and gluons.
- A key to this success are factorisation theorems in electron-proton scattering, which render part of the dynamics accessible to calculation in perturbation theory. The remaining non-perturbative quantities are the so-called diffractive parton distribution functions (dPDFs) and generalised (or “skewed”) parton distributions (GPDs). They can be extracted from measurements and contain specific information about small-x partons in the proton that can only be obtained in diffractive processes.
  Diffractive parton densities are determined from inclusive diffractive processes and can be interpreted as conditional probabilities to find a parton in the proton when the final state of the process contains a fast proton of given four-momentum. Generalised parton distributions can be accessed in exclusive diffractive processes; they quantify correlations between parton momenta in the proton. Their t-dependence is sensitive to the distribution of partons in the transverse plane.
- To describe hard diffractive hadron-hadron collisions is more challenging since factorisation is broken by rescattering between spectator partons. These soft re-interactions can produce additional final-state particles which fill the would-be rapidity gap. When such additional particles are produced, a very fast proton can no longer appear in the final state because of

energy conservation. The effect is often quantified in terms of the so called “gap survival probability”. These rescattering effects are of interest in their own right because of their intimate relation with multiple scattering effects, which at LHC energies are expected to be crucial for understanding the structure of events in hard collisions.

The dynamics of rescattering and multi-gap events is still not completely understood. The available data can be described in terms of an effective, non-linear Pomeron trajectory [251]; its variation with energy would be a consequence of multi-Pomeron exchange effects [252]. Other models, also testable at the LHC have been proposed (see e.g. [253] and references therein). These topics can be pursued in more detail with the CMS-TOTEM data at the LHC.

- A fascinating link has emerged between diffraction and the physics of heavy-ion collisions through the concept of saturation, which offers a new window on QCD dynamics in the regime of high parton densities.
- Perhaps unexpectedly, the production of a SM or MSSM Higgs boson in diffractive pp collisions is drawing more and more attention as a clean channel to study the properties of a light Higgs boson or even to discover it. The central exclusive reaction, $pp \to pHp$, appears particularly promising.

7.4.3. A survey of the accessible diffractive/forward processes

The accessible physics is a function of the integrated luminosity. We assume standard LHC optics with $\beta^* = 0.5$ m unless stated otherwise. We recall that, in this case, the TOTEM Roman Pots (RP) at 220 m from the CMS interaction point have coverage for $0.02 < \xi < 0.2$, where ξ is the proton fractional momentum loss. Near-beam detectors at 420 m from the interaction point, currently also being considered [254], would cover $0.002 < \xi < 0.02$.

Low-luminosity ($\sim 10^{28}$–$10^{30}\,\mathrm{cm^{-2}\,s^{-1}}$) studies could profit from running with $\beta^* > 0.5\,$m, where the ξ coverage of the 220 m RPs would be wider and the t resolution would improve because of the lower transverse momentum spread of the beam.

7.4.3.1. Inclusive single diffraction and double Pomeron exchange at low luminosity. At modest instantaneous luminosities, up to $10^{32}\,\mathrm{cm^{-2}\,s^{-1}}$, inclusive single diffractive (SD) events, $pp \to pX$, as well as inclusive double-Pomeron exchange (DPE) events, $pp \to pXp$, can be studied by requiring the presence of one or two rapidity gaps in the event. In the ξ range given above, the scattered proton can be detected and the kinematics of the events fully measured.

The inclusive SD and DPE cross sections, as well as their M_X dependence, even in the absence of a hard scale, are important quantities to measure at the LHC. Here M_X indicates the mass of the system X. These cross sections amount to approximately 15% and 1% of the total proton-proton cross section, respectively; their energy dependence is a fundamental parameter of (non-perturbative) QCD. In addition, since diffractive events constitute a major fraction of the pile-up events, their measurement is mandatory to be able to properly simulate and understand high-luminosity data, where, at instantaneous luminosities of $10^{34}\,\mathrm{cm^{-2}s^{-1}}$, approximately 35 pile-up events are superimposed, on average, to any event.

7.4.3.2. SD and DPE production of dijets, vector bosons and heavy quarks. The study of SD and DPE events in which the diffractively excited state includes high-E_T jets, heavy quarks or vector bosons opens up the possibility of accessing dPDFs and GPDs. The comparison of the DPE and SD rates for these processes may also give information on the hard diffractive factorisation breaking at LHC (see Section 7.4.2). A few examples of these processes are given here.

Production of dijets. The measurement of the reaction $pp \to pXjj$ (j indicates a jet) has been used for the first time by CDF to measure the diffractive structure function in antiproton-proton collisions [255]. A similar measurement is possible at LHC with wider kinematic coverage (CDF: $\xi > 0.035$) and larger minimum jet E_T. For $E_T > 45$ GeV, of the order of 10^8 events per fb^{-1} can be expected.

Production of heavy quarks. Inclusive DPE production of $t\bar{t}$ pairs has been studied in the case in which the final state contains one muon and four jets (i.e. with one top quark decaying to b plus lepton and neutrino, and the other to three jets). The analysis required the detection of both final-state protons. The expected number of events is of order $1 - 100$ for $10\,\text{fb}^{-1}$, depending on the theoretical model assumed.

SD and DPE production of B-mesons has also been looked at, with $B \to J/\psi X$ and $J/\psi \to \mu^+\mu^-$. Here the number of expected events is much larger, of the order of a few events per $10\,\text{fb}^{-1}$ in the DPE case and thousands in the SD case.

Inclusive DPE production of W bosons. Inclusive DPE production of W bosons, $pp \to pXWp$, is also sensitive to the dPDFs of the proton and is a relatively abundant process that can be studied at instantaneous luminosities where pile-up is small. In these conditions, the requirement that two final state protons be measured in the 220 m RPs suppresses both the QCD background and the inclusive W production. Several thousand events with $W \to e\nu$ or $W \to \mu\nu$ are expected, after cuts, for an integrated luminosity of $1\,\text{fb}^{-1}$. This process, in conjunction with SD production of W bosons, can be used to study hard diffractive factorisation breaking using the LHC data alone, as mentioned above.

7.4.3.3. SM and MSSM central exclusive Higgs production. As the delivered luminosity reaches tens of fb^{-1}, the central exclusive production process (DPE) becomes a tool to search for new physics, delivering signal to background ratios of order 0.1–1 for Standard Model (SM) Higgs production [256] and more than an order of magnitude larger for certain supersymmetric (MSSM) scenarios.

By central exclusive, we refer to the process $pp \to p\phi p$, where there are large rapidity gaps between the outgoing protons and the decay products of ϕ. There are three primary reasons why this process is attractive. Firstly, if the outgoing protons remain intact and scatter through small angles, then, under some general assumptions, the central system ϕ is produced in the $J_Z = 0$, C and P even state. Secondly, the mass of the central system can be determined very accurately from a measurement of the transverse and longitudinal momentum components of the outgoing protons alone. This means an accurate determination of the mass irrespective of the decay mode of the centrally produced particle. Thirdly, the process delivers excellent signal to background ratios, due to the combination of the $J_Z = 0$ selection rules, the mass resolution, and the simplicity of the event in the central detectors. An additional attractive property of central exclusive production is its sensitivity to CP violating effects in the couplings of the object ϕ to gluons.

The left panel of Fig. 7.14 shows the cross section times the branching ratio for central exclusive production of a Standard Model Higgs, with $H \to b\bar{b}$ and $H \to WW$, as a function of the Higgs mass for different theoretical approaches. The $b\bar{b}$ mode is particularly interesting for masses close to the current exclusion limit. The right panel of Fig. 7.14 shows the acceptance assuming various combinations of RPs at 220 m and near-beam detectors at 420 m. Both protons can be detected in the 220 m stations only for Higgs masses larger than $280\,\text{GeV}/c^2$; this reflects the ξ range for which the 220 m RPs have acceptance,

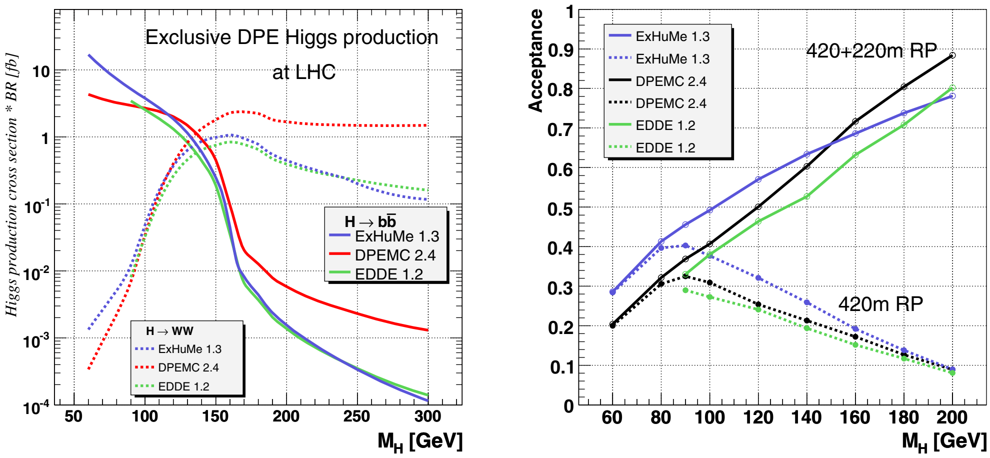

Figure 7.14. Left: The cross section for the exclusive production of the Higgs boson as a function of the Higgs boson mass for $H \to b\bar{b}$ and $H \to WW$. The different curves were obtained with the generators Exhume1.3 [259], DPEMC2.4 [260] and EDDE1.2 [261]. Right: Acceptance for the 420 m detectors alone and for the combination of the 220 m and 420 m detectors as a function of the Higgs boson mass.

$0.02 < \xi < 0.2$ (the mass of the centrally produced Higgs is related to the ξ via $M_H^2 = \xi_1 \xi_2 s$, with ξ_1, ξ_2 the fractional momentum losses of the two protons). However, asymmetric events with one proton at low ξ and another at large ξ can be detected by the combination of the 220 m and 420 m detectors ($0.002 < \xi < 0.02$).

Central exclusive production is generally an attractive way of searching for any new particles that couple strongly to glue. An example studied in [257] is the scenario in which the gluino is the lightest supersymmetric particle. In such models, there should exist a spectrum of gluino-gluino bound states which can be produced in the central exclusive channel. Likewise, central exclusive production of radions, the fields introduced in the Randall–Sundrum model of five-dimensional quantum gravity, has been studied [258].

$H \to b\bar{b}$. The analysis is based on the requirement of two back-to-back central b-tagged jets in addition to the detection of both final-state protons yielding a mass of the central system consistent with that calculated from the protons alone. The event yield is very low, about 2–4 events per 30 fb^{-1} after all cuts, depending on the model. The non-resonant continuum b-jet background is largely suppressed by the $J_Z = 0$ rule. The residual background, mostly due to dijet production ($gg \to$ dijets) and diffractive $gg \to b\bar{b}$ production, is a function of the mass resolution, which is about 1.6% for the '420 + 420' combination and 5.6% for the '220 + 420' combination (for $M_H = 120\,\text{GeV/c}^2$). The number of expected background events is of order 10 for 30 fb^{-1}.

$H \to WW$. In this case, the suppression of the background does not rely primarily on the mass resolution of the RPs. There are three main categories of WW events. Events in which at least one of the W bosons decays to an electron or a muon are the simplest, and pass the Level-1 trigger thanks to the high-p_T final-state lepton. This holds also if one of the W bosons decays into a tau, which subsequently decays leptonically. The four-jet mode occurs approximately half of the time; here, however, the RP information is necessary already at Level-1. The expected event yields range between 1 and 7 events for 30 fb^{-1}, depending on the mass. Irreducible backgrounds are small and controllable.

MSSM Higgs. Double proton tagging is especially beneficial in the MSSM case. The b-jet channel is very important in the 'intense coupling regime' of MSSM ($M_h \approx M_A \approx M_H \approx 100\,\mathrm{GeV/c^2}$) [262]: couplings of the Higgs to gg, WW^*, ZZ^* are strongly suppressed, making the discovery challenging by conventional means. Rates for central exclusive production of the two scalar (0^+) MSSM Higgs bosons (h, H) are more than a factor 10 larger than for the SM Higgs. The enhancement for $H \to b\bar{b}$ is by orders of magnitude in the M_h-max scenario for $M_H \approx 180$–$250\,\mathrm{GeV/c^2}$; likewise for $h \to b\bar{b}$ and $h \to \tau\tau$ for $M_h \approx 90$–$130\,\mathrm{GeV/c^2}$ [263]. In the small α_{eff} scenario, $h \to b\bar{b}$ and $h \to \tau\tau$ can be heavily suppressed for large $\tan\beta$ and for $M_h \approx 120\,\mathrm{GeV/c^2}$ [263], whereas $h \to WW$ may be enhanced by up to a factor 4 compared to the SM predictions. Also, the pseudo-scalar (0^-) Higgs boson (A) is practically not produced in the central exclusive channel, yielding a clean separation of the scalar and pseudo-scalar Higgs bosons, impossible in conventional channels. The good missing mass resolution allows to resolve h, H and, if enough statistics is available, measure their widths. This makes central exclusive production a possible discovery channel. Central exclusive production is also interesting in the '3-way mixing' scenario of CP-violating MSSM [264]: here the 3 neutral Higgs bosons are nearly degenerate, mix strongly and have masses close to $120\,\mathrm{GeV/c^2}$.

Central exclusive production, with its good mass resolution via the scattered protons, may allow disentangling the Higgs bosons by studying the production lineshape. Explicit CP-violation in the Higgs sector causes an asymmetry in the azimuthal distributions of tagged protons (via the interference of P-even and P-odd amplitudes) – a measurement unique at the LHC [262, 265].

7.4.3.4. High-energy photon interactions. A significant fraction of events at the LHC involves photon interactions at energies above the electroweak scale [266]. The protons radiating the photon often survive the collision intact and are scattered at angles comparable to the beam angular divergence. Detection of such events at the LHC will open up a new field of high-energy photon physics, which is briefly outlined below. By requiring the detection of one or two forward protons like in diffractive interactions, photon-photon and photon-proton interactions can be selected. The photon fluxes, and the effective luminosities of photon-photon and photon-proton collisions are well known [267, 268]. The average proton energy loss is larger and the proton scattering angle smaller in photon exchanges than for the diffractive case. This can be used to establish relative contributions of these two processes.

Two-photon exclusive production of W and Z boson pairs. The cross section for the production of W pairs via photon-photon interactions, $pp \to ppWW$, is slightly above 100 fb; in almost half of these events both forward protons are produced within the acceptance of the TOTEM RPs. About 100 events per $10\,\mathrm{fb}^{-1}$ with leptonic W decays can be detected in CMS. This allows a precise study of the gauge couplings, in particular of the $\gamma\gamma WW$ coupling. The expected sensitivity to anomalous quartic gauge couplings (QGCs) will surpass the LEP and Tevatron limits by orders of magnitude. A deviation from the Standard Model predictions would also allow a clean detection of anomalous WW production as predicted e.g. by A. White's theory of the supercritical Pomeron [269]. Two-photon production of Z pairs, $pp \to ppZZ$, is not allowed at the SM tree level, but yields similar sensitivities to the anomalous QGCs in this channel.

Two-photon exclusive production of pairs of SUSY particles. The cross sections for production of pairs of charginos, sleptons and charged Higgs bosons via photon-photon fusion at the LHC decrease rapidly with the masses of these particles [269]. This limits the scope of SUSY searches to particle masses below 150–200 GeV/c^2. However, the very clean environment of this reaction makes it attractive compared to other production mechanisms; the final state typically consists of two opposite-sign leptons and of missing p_{T}. The main background is due to the exclusive production of W pairs discussed above.

Two-photon production of doubly charged Higgs bosons (appearing in GUTs) is strongly enhanced, and leads to exclusive final states with two pairs of same-sign leptons.

Two-photon lepton pair production. Exclusive production of lepton pairs – a purely QED process at low $|t|$ – may serve for calibration of the pp luminosity; it may also be used for calibration of the momentum measurement of the scattered proton. Thousands of exclusive muon pairs are expected to be reconstructed in CMS for an integrated luminosity of 1fb^{-1}. The striking signature of extremely small muon acoplanarity angles of less than about 10 mrad may be exploited already at the trigger level.

Single W and single top photoproduction. The cross section for single W photoproduction, $pp \to pWjX$, reaches almost 100 pb. This process can be therefore studied already at low luminosity. It also provides a means to study rescattering effects [268]. At higher luminosities, studies of high mass Wj states will be possible; for Wj invariant masses above 1 TeV, tens of events are expected to be detected in CMS (and tagged by TOTEM) per 10 fb^{-1}. This will allow to search for, as an example, an anomalous triple gauge coupling γWW. This process is the main background in the search for anomalous photoproduction of single top.

Associated WH and top pair photoproduction. The associated photoproduction of a SM Higgs boson and a W boson has a cross section of about 20 fb for Higgs mass below 180 GeV/c^2. About 50% of the forward protons are tagged by TOTEM, and events with leptonic W decay can be triggered efficiently in CMS. The cross section for photoproduction of top pairs is slightly above 1 pb. Top pair production is the main background for WH production, and in the photoproduction case the signal-to-background ratio for photoproduction of WH pairs is superior to the one in inclusive production.

7.4.3.5. Drell–Yan. The study of forward production of low mass Drell–Yan lepton pairs at the LHC provides a unique opportunity to directly access low-x partons in the proton. In this process, the lepton pair originates from the annihilation of a quark-anti-quark pair whose fractional momenta, x_1 and x_2, are related to the dilepton mass, M, and rapidity, y, through

$$M^2 = sx_1x_2; \qquad x_{1,2} = \frac{M}{\sqrt{s}}\exp^{\pm y}, \tag{7.2}$$

with $\sqrt{s} = 14$ TeV, the centre-of-mass energy of the colliding protons. In order to access low x, a large imbalance in fractional momenta is required, boosting the lepton pair to large rapidities.

The CASTOR calorimeter will cover the pseudorapidity range $5.3 < \eta < 6.6$, corresponding to Bjorken-x values down to 10^{-7}. With CASTOR alone, it may be possible to obtain a crude estimate of the dilepton mass. With the additional information provided by the T2 tracker, one can enhance the signal to background ratio by requiring tracks in association to the electromagnetic energy deposits. As T2 will measure both the azimuthal and polar angles of the tracks, a much more accurate measurement of the opening angle (and therefore of the dilepton mass) and a two-dimensional study in M^2 and x will become possible.

7.4.3.6. Validation of cosmic-ray generators. The correct simulation of the interaction of primary cosmic rays in the PeV energy range with the atmosphere is a key tool in the study of cosmic rays. Unfortunately, the available generators differ significantly in their predictions for the energy flow, multiplicity, hadronic energy fraction etc., in particular at high rapidities. These models can be tested at the LHC: a 100 PeV fixed-target collision in air corresponds to the centre-of-mass energy of a pp collision at the LHC. Several generators were used to simulate inelastic and diffractive collisions at CMS: QGSJET [271], SIBYLL [272], DPMJET [273], NEXUS [271]. There are significant differences in the predictions, notably in the region covered by CASTOR, T1 and T2. A measurement of these features with CASTOR, T1 and T2 may thus be used to validate/tune these generators.

7.5. Physics with heavy ions

7.5.1. High-density QCD: heavy-ion physics

Quantum Chromodynamics (QCD) is the only existing quantum field theory within the Standard Model, whose collective behaviour, phase diagram and phase transitions, are accessible to study in the laboratory. High-energy nucleus-nucleus collisions offer the only experimental means known so far to concentrate a significant amount of energy ($\mathcal{O}(10\,\text{TeV})$ at the LHC) in a "large" volume ($\mathcal{O}(100\,\text{fm}^3)$ at thermalisation times of $\tau_0 \approx 1\text{fm}/c$), allowing the study the many-body dynamics of strongly interacting matter. The programme of high-energy heavy-ion physics addresses several key open questions of the strong interaction:

- **Deconfinement and chiral symmetry restoration.** Lattice QCD calculations predict a new form of matter at energy densities above $\varepsilon \approx 1\,\text{GeV/fm}^3$ consisting of an extended volume of deconfined and bare-mass quarks and gluons: the Quark Gluon Plasma (QGP) [274]. The scrutiny of this new state of matter (equation-of-state, order of the phase transition, ...) promises to shed light on fundamental questions such as the nature of confinement, the mechanism of mass generation (chiral symmetry breaking, structure of the QCD vacuum) and hadronisation, that still evade a thorough theoretical description due to their highly non-perturbative nature.
- **Non-linear parton evolution at small-x.** At high energies, hadrons consist of a very dense system of gluons with small (Bjorken) parton fractional momenta $x = p_{parton}/p_{hadron}$. At low-$x$, the probability to emit an extra gluon is large $\sim\alpha_S \ln(1/x)$ and non-linear gluon-gluon fusion processes start to dominate the parton evolution in the hadronic wave functions. Whereas at values of $x \gtrsim 10^{-3}$, the parton evolution with Q^2 (or $\ln(1/x)$) is described by the usual DGLAP (or BFKL) equations, at lower values of x and around $Q_s^2 \sim 3\,GeV^2/c^2$, such a saturated configuration is theoretically described in terms of the "Colour Glass Condensate" (CGC) picture [275]. Since the nonlinear growth of the gluon density depends on the transverse size of the system, the effects of gluon saturation are expected to set in earlier (at higher x) for heavy nuclei than for free nucleons.

In addition, the study of heavy-ion collisions has interesting connections to other research areas such as:

- **Early Universe cosmology.** The quark-hadron phase transition took place some 10 μs after the Big-Bang and was the most important event taking place in the Universe between the electro-weak (or SUSY) transition ($\tau \sim 10^{-10}$ s) and Big Bang nucleosynthesis (BBN, at $\tau \sim 200$ s). Depending on the order of the QCD phase transition, several cosmological implications such as the formation of strangelets and cold dark-matter (WIMP) clumps or baryon fluctuations leading to inhomogeneous nucleosynthesis, have been postulated [276].

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