The Compact Muon Solenoid Experiment
Conference Report

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

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Forward physics with the CMS experiment at the LHC

Thomas McCauley

Abstract

Forward physics to be investigated with CMS at the LHC includes a wide range of topics, including low- x QCD, diffractive scattering, and constraints of cosmic ray Monte Carlo predictions for multi-particle production. We describe the forward detection instrumentation around the CMS interaction point and present selected feasibility studies to illustrate the physics potential.

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1 The Large Hadron Collider and CMS

The Compact Muon Solenoid (CMS) [1] is one of two general-purpose detectors¹⁾ located at the Large Hadron Collider (LHC) at CERN. At each interaction point the LHC will eventually provide proton-proton collisions at $\sqrt{s} = 14$ TeV with a design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to an integrated luminosity of 100 fb^{-1} per year. In addition to p-p collisions the LHC will also eventually provide p-Pb (Pb-Pb) collisions at $\sqrt{s} = 8.8$ (5.5) TeV.

The CMS central detector is designed primarily for efficient detection and precise measurement of phenomena at high transverse momentum. CMS therefore combines a central tracking system, electromagnetic and hadronic calorimetry and muon triggering and identification. The effective coverage for particle detection extends to a polar angle of about $|\theta| = 1^\circ$ from the beam axis and in pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ up $|\eta| = 5$.

2 Forward detectors around IP5

In addition to the central CMS detector itself, the instrumentation around the CMS interaction point (IP5) also boasts a full complement of forward detectors, *i.e.* covering the kinematic region at small polar angles and large values of rapidity (the maximum possible rapidity at the LHC in proton-proton collisions at $\sqrt{s} = 14$ TeV is $y_{max} = \ln(\sqrt{s}/m_\pi) \sim 11.5$). A schematic view of the forward detectors can be seen in Fig. 1. Forward instrumentation in the CMS experiment consists of the forward hadronic calorimeter (HF), the CASTOR and ZDC calorimeters. A separate experiment TOTEM further extends the forward reach. All together with the central CMS detector, the detectors at IP5 will provide unprecedented coverage in pseudorapidity at a hadron collider, with coverage from $\eta = 5$ extending up to $\eta \sim 10$. The proposed FP420 detectors would further complement the forward physics capabilities available around the CMS interaction point.

Figure 1: Schematic of the forward detector instrumentation around the CMS interaction point. The detectors of the CMS experiment include the central detector, HF, CASTOR, and the ZDC. The detectors of TOTEM are T1, T2, RP 147, and RP 220. See text in this section for further description of the detectors.

2.1 HF

The HF (hadronic forward) calorimeter is a steel and quartz fiber calorimeter 11.2 m from IP5 covering the pseudorapidity range $3 < |\eta| < 5$ with 1200 towers over the intervals $\Delta\eta \times \Delta\phi \sim 0.175 \times 0.175$. It extends over 10 interaction lengths.

2.2 CASTOR

The CASTOR (Centauro and Strange Object Research) detector is a quartz-tungsten sampling calorimeter located 14.38 m from IP5 which will cover the pseudorapidity region $5.25 < |\eta| < 6.5$. CASTOR comprises separate electromagnetic and hadronic sections and 16 azimuthal and 14 longitudinal readout segments over a total depth

¹⁾ For information on ATLAS see the contribution of M.T. Dova in these proceedings.

of 10.3 interaction lengths; there is no segmentation in η . At the start-up of the LHC there will be a CASTOR on only one side of the interaction point.

2.3 ZDC

The Zero Degree Calorimeter (ZDC) is a quartz fiber and tungsten sampling calorimeter installed on both sides of IP5 at a distance of 140 m. It will provide detection coverage in the pseudorapidity region $|\eta| > 8.1$ for neutrals and photons. Each ZDC is made up of separate electromagnetic (19 radiation lengths over 5 horizontal readout units) and hadronic (4 horizontal readout units) sectors over a total depth of 6.5 interaction lengths. Both calorimeters of the ZDC are installed at their respective positions on either side of the interaction point and will be ready for data-taking at the start-up of the LHC.

2.4 TOTEM and FP420

TOTEM [2] is a separate experiment at the CMS interaction point. Its main objective is the measurement of the proton-proton elastic cross section and, to a precision of $\sim 1\%$, the total cross section. TOTEM and CMS have also planned a joint physics program; further details can be found in Sec. 3 and in [3]. TOTEM comprises several detectors installed symmetrically around IP5. The T1 telescope is located in front of HF and consists of 5 planes of cathode strip chambers. T2 is located in front of CASTOR and consists of 10 planes of gas electron multipliers. Further down the beam pipe at ± 147 m and ± 220 m are proton taggers consisting of silicon strip detectors housed in roman pots (RPs).

FP420 [4] is a proposed detector providing proton tagging at ± 420 m from either the CMS or ATLAS interaction point. A research and development program is under review by the CMS and ATLAS collaborations. The physics program of FP420 would include Higgs central exclusive production, determination of the quantum numbers of the Higgs, hard diffraction, as well as γp and $\gamma\gamma$ physics.

3 Physics program

The CMS physics program includes searches for the Higgs boson, studies of electroweak physics, top physics, searches for supersymmetry and exotic phenomena, studies of QCD, heavy ions, and diffractive and forward physics.

Extending the physics reach of CMS, the program for diffractive and forward physics (see [5] for a recent summary) includes studies of hard diffraction, low- x QCD, constraints on hadronic models used in ultra-high energy cosmic ray physics, photon-photon physics (*e.g.* exclusive dilepton production), discovery physics (*e.g.* MSSM Higgs), and precision measurements with central exclusive production.

3.1 Diffraction

Diffractive p-p events are characterized by colorless exchange mediated by a Pomeron where one or both of the incoming protons emerge intact in the final state and by the presence of large rapidity gaps devoid of hadronic production. Hard diffractive processes can be described with perturbative QCD and the cross sections can be factorized into generalized parton distributions and diffractive parton distribution functions (dPDFs). These dPDFs contain information about low- x partons and motivate the interest in hard diffractive processes. Also of interest is the “rapidity gap survival probability” $\langle |S^2| \rangle$ [6], which quantifies the break-up of the factorization due to scattering between spectator partons. At the Tevatron, $\langle |S^2| \rangle$ was found to be $\mathcal{O}(1\%)$ [7]. Theoretical estimates for the LHC vary from a fraction of a percent to as much as 30% [8].

In hard diffractive processes high mass or large p_T states are possible. These can include the production of jets, heavy flavors, W, and Z. Of particular interest here is the single diffractive process $pp \rightarrow pX$, where X includes either a W or two jets. Observation of such events exploit the asymmetry of the particle multiplicity in η for diffractive events, as there is an expected lower multiplicity in the region of η that contains the scattered proton. In addition, diffractive events are characterized by a multiplicity distribution as observed in the central tracker (for $|\eta| < 2$) that peaks at lower values than for non-diffractive events.

3.1.1 Single-diffractive W production

Observation and study of single-diffractive W events would allow for measurement of the diffractive to inclusive W production yields, would provide information on the rapidity gap survival probability, and is sensitive to the quark content of the dPDFs in a region previously unstudied.

Shown in Fig. 2 [9] is the number of active calorimeter towers (above noise level) in CASTOR and HF for events for $W \rightarrow \mu\nu$. A rapidity gap survival probability of 5% is assumed for the diffractive event sample (where the POMWIG generator was used) and the number of events is normalized to an integrated luminosity of 100 pb^{-1} where no pile-up is present. The diffractive peaks can clearly be seen in the regions of no activity in CASTOR and HF and demonstrate the feasibility of observing single diffractive W production. Further improvements are expected with the inclusion of TOTEM.

Figure 2: Number of calorimeter towers in CASTOR and HF with activity for single diffractive W events. The plots with only POMWIG (*i.e.* the upper two) indicate events with hard diffraction only, the plot with PYTHIA only (lower left) indicates events with no hard diffraction, and the lower right plot indicates the contribution of hard diffraction to the events at lower left.

3.1.2 Single-diffractive dijet production

Complementing the study of single-diffractive W production, the single-diffractive production of dijets can provide information on the value of $\langle |S^2| \rangle$ and is sensitive to the gluon content of the dPDFs. Observation of such events proceeds along the same lines as that of single-diffractive W production: the detection of large rapidity gaps using HF and CASTOR, complemented by multiplicity information in the central tracker. $\mathcal{O}(300)$ signal events (*i.e.* those in the $[0,0]$ bin in two-dimensional multiplicity plots of the type shown in Fig. 2) are expected [10] per 10 pb^{-1} of integrated luminosity (with $S/B \sim 30$), assuming a rapidity gap survival probability of 5%. Signal observation at this level would exclude very low values of $\langle |S^2| \rangle$.

3.2 Low- x QCD

The forward instrumentation around CMS will allow for a continuation of studies of deep inelastic scattering in e-p collisions at HERA, where low- x dynamics have been studied down to values of 10^{-5} . For decreasing x the corresponding observed increase in gluon density is described by the DGLP [11] and BFKL [12] evolution equations which govern parton radiation in Q^2 and x , respectively. Eventually at low enough x non-linear (gluon-gluon) fusion effects become important, where saturation effects tame the rise in proton gluon density.

At the LHC the minimum accessible x in proton-proton collisions decreases by a factor of ~ 10 for each 2 units of rapidity; in processes with a hard scale of $Q \sim 10 \text{ GeV}$ and within detector acceptance values of x as low as 10^{-6} can be probed. Such processes include the production of forward jets and of Drell-Yan production of e^+e^- pairs.

3.2.1 Forward jets in HF

Measurement of forward jets in HF can provide information on the underlying parton distribution functions at low- x in the proton. Detailed analysis of fully simulated and reconstructed jets for p-p events at $\sqrt{s} = 14 \text{ TeV}$ for

an integrated luminosity of 1 pb^{-1} shows that a p_T resolution of $\sim 19\%$ at 20 GeV and $\sim 10\%$ at 100 GeV is attainable [13]. If the systematic uncertainty in the calibration of the jet energy scale can be reduced to the 5% level then measurement of forward jets can help to constrain the underlying PDF in global fit analyses. Further studies of QCD [15], particularly BFKL-like dynamics, are possible with Mueller-Navelet dijet [14] events, characterized by jets with similar p_T separated by a large rapidity gap ($\Delta\eta \sim 6-10$). This study will eventually be extended to use CASTOR, furthering the kinematic reach.

3.2.2 Drell-Yan pairs detected in T2/CASTOR

The detection and measurement with T2/CASTOR of forward electron pairs produced via the Drell-Yan process can allow for probes of quark densities down to $x_1 \sim 10^{-6}$ [3]. Shown in Fig. 3 is the distribution of the invariant mass M of the e^+e^- system versus the x of one of the quarks (where x_2 is chosen such that $x_1 \gg x_2$). The region between the dotted lines indicates the acceptance region for detection of both electrons in T2/CASTOR and the solid curve indicates the kinematic limit. The black points correspond to any of the Drell-Yan events generated with PYTHIA. The green (light grey) points indicate the events where at least one of the electrons lies within the T2/CASTOR acceptance; the blue (dark grey) points are for events where both electrons lie in the acceptance.

Figure 3: Acceptance of Drell-Yan electrons in the T2/CASTOR detectors. See text for details.

As mentioned above, QCD saturation effects can arise for low enough x . These effects may manifest in the Drell-Yan production cross sections in the T2/CASTOR acceptance; Drell-Yan pairs can be suppressed by a factor of 2 when using a PDF with saturation effects compared to one without [3].

3.3 Exclusive dilepton production

Exclusive dilepton production is a process characterized by either an e^+e^- or $\mu^+\mu^-$ pair produced where the beam protons remain intact and escape undetected down the beam pipe. The two processes that contribute to this process are shown in Fig. 4; both possess similar experimental signatures. The inelastic background of this process, where one of the protons dissociates, can be mitigated by use of a veto condition on activity in CASTOR and ZDC.

With an event sample from the 100 pb^{-1} of data several measurements are possible. Exclusive dimuon production is an ideal channel for alignment of forward proton detectors. Exclusive dilepton production via $\gamma\gamma \rightarrow l^+l^-$ is a nearly pure QED photon exchange process with a well known production cross section that can potentially provide a calibration sample for luminosity (a 4% precision might be feasible) and for studies of lepton identification [16]. In addition, the cross section of the upsilon photoproduction process is sensitive to the generalized parton distribution function for gluons in the proton. Measurement of the p_T^2 distribution of Υ can be used as an estimator of the t (the four-momentum transfer at the Pomeron-proton vertex) dependence of the cross section.

3.4 Constraints on ultra-high energy cosmic ray interaction models

The measured energies of the ultra-high energy cosmic rays extends up to 10^{20} eV and beyond [17]. Determination of the primary energy and content of the ultra-high energy cosmic rays relies on hadronic Monte Carlo (MC) codes

Figure 4: Diagrams of exclusive dilepton processes: elastic $\gamma\gamma \rightarrow l^+l^-$ (upper) and $\gamma p \rightarrow \Upsilon \rightarrow l^+l^-$ (lower).

which describe the interactions of the primary cosmic-ray in the upper atmosphere. The bulk of the primary particle production is dominated by forward and soft QCD interactions, modeled commonly in Regge-Gribov-based approaches [18] [19] with parameters constrained by the existing collider data ($E_{lab} < 10^{15}$ eV).

When extrapolated to energies up to the highest observed, the current MCs predict energy and multiplicity flows differing by factors as large as three, as seen in Fig. 5, with significant inconsistencies in the forward region. Measurement of forward particle production in p-p, p-Pb, and Pb-Pb collisions at LHC energies ($E_{lab} \approx 10^{17}$ eV) can provide strong constraints on these models and allow for more reliable determinations of the cosmic ray energy and composition at the highest energies.

Figure 5: Energy flow predictions for diffractive p-p events at $\sqrt{s} = 14$ TeV for several cosmic ray hadronic interactions models in CASTOR[3].

4 Outlook

This year should see the long-anticipated turn-on of the LHC with first collisions expected for the autumn. The full coverage of detectors in η will be unprecedented at a hadron collider. In addition to the physics available in the high p_T region with the central CMS detector, the CMS and TOTEM forward detectors around the interaction point will provide complementary and rich physics to the overall program.

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