The Compact Muon Solenoid Experiment
Conference Report

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

27 November 2008

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Ada Solano, on behalf of the CMS Collaboration

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Presented at *DIFFRACTION 2008*, September 9-14, 2008, La Londe-les-Maures, France, 05/12/2008

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Ada Solano, on behalf of the CMS Collaboration

University of Torino and INFN-Torino, via Giuria 1, I-10125 Torino

Abstract. A rich program of forward physics, including very low- x QCD dynamics, photon-induced processes, underlying event and energy flow distributions, diffraction in the presence of a hard scale and even the Higgs boson search in central exclusive production, is being studied by the CMS Collaboration, taking advantage of the forward detector instrumentation around the CMS interaction point at the LHC.

FORWARD DETECTORS AND FORWARD PHYSICS AT CMS

The diverse physics subjects under the name of forward physics have in common that particles produced at small polar angles θ and hence large values of rapidity provide a defining characteristics.

At the Large Hadron Collider (LHC) proton-proton collisions will occur at 14 TeV, with a maximal possible rapidity $y_{max} = \ln \frac{\sqrt{s}}{m_\pi} \sim 11.5$. The CMS experiment [1], primarily designed for efficient detection of high transverse momentum particles produced at central rapidities, has the main calorimetric and tracking components which cover a range in pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ extending to $|\eta| = 5$, including the Hadron Forward (HF) calorimeter. Further coverage in the forward region is provided by the CASTOR and ZDC calorimeters.

At the same interaction point of CMS (IP5) the TOTEM [2] experiment is located, designed for the measurement of the total cross section with a precision of approximately 1%. TOTEM has part of its forward tracking devices inside the volume of the main CMS detector, plus near-beam proton taggers at a distance up to ± 220 m from IP5. The physics potential of a joint CMS-TOTEM data taking, which would require a common data acquisition system not available at the moment, has been presented in [3].

After an overview of the forward instrumentation around IP5, a few selected studies are presented on very low- x QCD dynamics, photon-induced processes, underlying event and energy flow distributions, diffraction in the presence of a hard scale.

Proton taggers and their physics potential, in particular the possible Higgs boson discovery in central exclusive production, is discussed separately in the next section.

Forward detectors at IP5. A layout of the forward detectors up to ± 220 m from IP5 is shown in Fig. 1. The central detector consists of a tracking system ($|\eta| \leq 2.5$), an electromagnetic ($|\eta| \leq 3$) and a hadronic calorimeter ($|\eta| \leq 5$), all embedded in a solenoidal magnetic field of 4 T, and a muon system ($|\eta| \leq 2.4$). The HF calorimeters, made of steel absorbers and radiation-hard quartz fibers for the fast collection of Cherenkov light, cover the regions $3 \leq |\eta| \leq 5$. The TOTEM telescopes T1, which consist of Catho-

FIGURE 1. A layout of the forward instrumentation around IP5

de Strip Chambers (CSCs), are located on both sides of the IP5 right in front of the HF and with a similar η coverage.

The CASTOR calorimeter, currently installed only on one side of IP5, significantly enhances the CMS forward hermeticity to $5.2 \leq |\eta| \leq 6.6$. It is a Cherenkov sampling calorimeter with tungsten plates as absorbers and fused silica quartz plates as active media. It has an electromagnetic and a hadronic section, and it is segmented azimuthally in 16 sectors and longitudinally in 14 layers, while there is no segmentation in η . The TOTEM telescopes T2, which consist of Gas Electron Multiplier (GEM) detectors mounted on both sides of IP5, provide tracking in front of the CASTOR calorimeters, with a similar η coverage.

Outside the main CMS volume, on both sides of IP5, the Zero Degree Calorimeters (ZDCs) allow to measure neutral particles at $|\eta| > 8.1$ with very high acceptance. They also are Cherenkov tungsten-quartz calorimeters, with an electromagnetic and a hadronic section, located ± 140 m away from IP5, where the LHC beampipes separate.

Finally, the layout in Fig. 1 shows the Roman pot stations of TOTEM, located at ± 147 m and ± 220 m from IP5, and the possible FP420 [4] detectors, which would be located at ± 420 m. These proton taggers are described in the next section.

Low- x dynamics. At the LHC, measurements in the forward direction can be used as means to access parton structure and evolution of the proton at values of Bjorken- x as low as $x \sim 10^{-6}$, since the minimum accessible x decreases by a factor ~ 10 every two units of rapidity.

A direct access to the quark densities of the proton at low- x values is given by the measurement of lepton pair (Drell-Yan) production $q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$. To be sensitive to the low- x regime at reasonably large values of the e^+e^- mass, a large imbalance in fractional momenta is required, boosting the lepton pair to large rapidities, within the acceptance of the T2/CASTOR detectors. Generator level studies of Drell-Yan production have also shown sensitivity to saturation. Since the rapid rise of the gluon density in the proton with decreasing x cannot continue indefinitely without violating unitarity, saturation effects are expected at some point at low- x , leading to non-linear terms in the QCD parton evolution, which should be measurable.

Complementary information on the QCD dynamics at low- x values can be obtained from high energy forward jets, which are sensitive to BFKL evolution, where no ordering in transverse momentum is assumed, leading to hard partons produced at the beginning of the cascade, close to the proton i.e. in the forward direction, within the CASTOR acceptance. Also the Müller-Navalet dijet events are particularly sensitive to BFKL dynamics because the large rapidity separation between the two jets enhances the available phase space for BFKL-like parton radiation. More information concerning the CMS studies on forward jets can be found in [5].

Multiplicity, energy flow and cosmic ray physics. Measurements of multiplicity and energy flow distributions will be of great importance in the early stage of data taking for tuning Monte Carlo parameters, in order to take correctly into account underlying event contributions and multiple parton interactions, where additional soft and hard interactions between spectator partons and initial and final state radiation occur. Studies at the generator level indicate that the kinematical region covered by the forward detectors is especially sensitive to features of these events which central detector information alone cannot constrain.

Energy measurements in the forward detectors will also be important to validate Monte Carlo generators of high energy cosmic-rays. In fact, 100 PeV energy for a fixed target collision in air corresponds to the centre of mass energy of a pp collision at the LHC. Studies at the generator level have shown that there are significant differences in the Monte Carlo predictions, notably in the region covered by CASTOR/T2 and ZDC.

Diffraction with a hard scale. A substantial fraction of pp interactions consists of diffractive reactions, $pp \rightarrow pXp$ or $pp \rightarrow pX$, characterized by the fact that the incoming proton(s) emerge from the interaction intact, or excited into a low mass state, with an energy loss of only a few per cent. Diffractive processes, as described by Regge theory, are dominated by a t -channel exchange with vacuum quantum numbers, the so-called pomeron, now also understood in terms of partons from the proton. A fast proton in the final state can also originate from the exchange of a photon, as discussed later.

The absence of colour flow between the proton(s) and the system X results in the topological signature of these events, i.e. large gap(s) in the rapidity distribution of the hadronic final state. There are thus two ways for selecting these events: either by requiring the absence of signal in the forward detectors, valid only at low luminosity, without pile-up events, or by measuring the scattered proton(s) with near-beam taggers.

Diffractive reactions are predominantly soft but can also occur in the presence of a hard scale, as observed at UA8, HERA and Tevatron. The hard scale may be provided by jets, heavy quarks or the W or Z boson mass and allows perturbative QCD (pQCD) to be used. Cross sections can then be factorized into a partonic cross section, which describes the hard scattering and is calculable in pQCD, times a diffractive parton distribution function (dPDF), which can be interpreted as proton PDF under the condition that the proton remains intact. Diffractive processes are thus additional tools to study the structure of the proton.

In hadron-hadron collisions factorization is broken by rescattering between spectator partons, which fill the large rapidity gap (LRG). The resulting suppression of the diffractive cross section is quantified by the rapidity gap survival probability, S^2 , which is an

important ingredient to be measured at the beginning of the LHC data taking. Rescattering effects are also related to multiple parton interactions which are expected to be crucial for understanding the structure of the underlying events.

A few preliminary studies with full detector simulation and reconstruction have been performed by the CMS Collaboration which demonstrate the feasibility of measuring hard diffraction with the first 100 pb^{-1} of integrated luminosity, in a zero pile-up scenario which allows a rapidity gap based selection [6, 7, 8]. More details can be also found in [9].

Single diffractive W production $pp \rightarrow pWX$ has been studied in the decay channel $W \rightarrow \mu\nu$. This process is mainly sensitive to the quark dPDFs and probes S^2 , since the cross section is directly proportional to it. Requiring no activity above noise level in HF and CASTOR, and using a value of $S^2 = 5\%$, a signal to background ratio of ~ 20 can be obtained, with $\mathcal{O}(100)$ events in 100 pb^{-1} .

The exclusive production of Y vector mesons in γp fusion has been studied in the decay channel $Y \rightarrow \mu^+\mu^-$. This process is sensitive to the two-dimensional distribution of the gluons in the transverse plane and would give access to the generalized parton distribution functions (GPDs). It would also serve for the calibration and alignment of the proton taggers.

$\gamma\gamma$ physics. The LHC can also be considered a $\gamma\gamma$ collider, opening up a new field of high energy photon physics. The protons radiating the photon often survive the collision intact and the resulting events, $pp \rightarrow p(\gamma\gamma)p \rightarrow pXp$, show the same topology as the diffractive ones, with a smaller average proton scattering angle and a larger average proton energy loss, such that the $\gamma\gamma$ centre of mass energy can reach values beyond 1 TeV.

A very interesting $\gamma\gamma$ process is exclusive dilepton production, $pp \rightarrow p(\gamma\gamma)p \rightarrow pl^+l^-p$, where $l^+l^- = e^+e^-, \mu^+\mu^-$, which has been studied by the CMS Collaboration with full detector simulation and reconstruction, in an early data taking scenario with no pile-up events [8]. Requiring exclusivity conditions in central detectors and no activity above noise level in CASTOR and ZDC, $\mathcal{O}(700) \mu^+\mu^-$ events and $\mathcal{O}(70) e^+e^-$ events can be obtained in 100 pb^{-1} of data. Since this QED cross section is very precisely known, the process can be used for an absolute luminosity measurement, with a 4% precision with 100 pb^{-1} of data. This process is also a valid candidate for the calibration and alignment of the proton taggers.

PROTON TAGGERS AND THEIR PHYSICS POTENTIAL

At high luminosities at the LHC, with overlaid pile-up events filling the large rapidity gap, tagging the scattered proton(s) will be the only way of selecting diffractive events and $\gamma\gamma$ processes. To this purpose, the LHC beamline with its magnets can be considered as a spectrometer, which bends the slightly off-momentum scattered protons enough to be measured in small tracking detectors inserted into the beampipe far from the interaction point.

Proton tagger detectors. At ± 147 and ± 220 m from IP5, TOTEM has silicon detectors approaching the beam inside movable Roman pot stations. With nominal LHC beam optics, the acceptance covers the kinematical region $0.02 < \xi < 0.2$, where ξ is the fractional momentum loss of the scattered proton with respect to the incident proton. The advantages of a common CMS-TOTEM data taking have been presented in [3].

In order to achieve acceptance at smaller ξ values and thus tag diffractive protons, a new detector, FP420, has been proposed [4], which would be located at ± 420 m from the interaction point, in the cryogenic region of the LHC. The proposal is being reviewed by CMS and a TDR is in preparation.

FP420 foresees a movable beampipe, housing stations of 3D silicon detectors, an extremely radiation hard novel technology, and Cherenkov timing detectors, with a resolution of the order of ~ 10 ps to relate the tagged proton to the interaction vertex and filter out protons from pile-up events. The foreseen distance of approach to the beam for the Si detectors is 3 mm, resulting in an acceptance for protons with $0.002 < \xi < 0.02$.

Physics potential. Forward proton tagging capabilities would strongly enhance the physics potential of CMS, allowing, among other things, a very interesting QCD program on hard diffraction at high luminosities and precision measurements of high energy exclusive $\gamma\gamma$ reactions $pp \rightarrow p(\gamma\gamma)p \rightarrow pXp$, where $X = \gamma\gamma, l^+l^-, WW, ZZ, H, tt$ or a SUSY-pair. In particular, W -pair production is sensitive to the quartic gauge couplings.

A relevant physics case for FP420 is central exclusive production (CEP), $pp \rightarrow p \oplus \phi \oplus p$, where $\oplus$ indicates the presence of a LRG and ϕ could in particular be the Higgs boson.

The measurement of both protons gives the possibility to determine the mass of the state ϕ with an excellent resolution, independent of the decay products. For a light Higgs, decaying in $b\bar{b}$, proton tagging improves the signal/background ratio dramatically. Moreover, it has been shown that in certain regions in MSSM, CEP might be the discovery channel for the Higgs boson. More information about the physics potential of FP420 can be found in [4].

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