Forward detectors around the CMS interaction point at LHC and their physics potential

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Forward physics with CMS at the LHC covers a wide range of physics subjects, including very low-$x_{Bj}$ QCD, underlying event and multiple interactions characteristics, $\gamma$-mediated processes, shower development at the energy scale of primary cosmic ray interactions with the atmosphere, diffraction in the presence of a hard scale and even MSSM Higgs discovery in central exclusive production. We describe the forward detector instrumentation around the CMS interaction point and present selected feasibility studies to illustrate their physics potential.

1. FORWARD PHYSICS AND FORWARD INSTRUMENTATION AT THE CMS INTERACTION POINT

Forward physics at the LHC covers a wide range of diverse physics subjects which have in common that particles produced at small polar angles $\theta$ and hence large values of rapidity provide a defining characteristics. This article concentrates on their physics interest in $pp$ collisions.

At the Large-Hadron-Collider (LHC), where proton-proton collisions occur at center-of-mass energies of 14 TeV, the maximal possible rapidity is $y_{\text{max}} = \ln \frac{\sqrt{s}}{m_\pi} \sim 11.5$. The two multipurpose detectors ATLAS and CMS at the LHC are designed primarily for efficient detection of processes with large polar angles and hence high transverse momentum $p_T$. The coverage in pseudorapidity $\eta = -\ln |\tan (\theta/2)|$ of their main components extends down to about $|\theta| = 1^\circ$ from the beam axis or $|\eta| = 5$.

For the CMS detector, several subdetectors with coverage beyond $|\eta| = 5$ are currently under construction (CASTOR and ZDC sampling calorimeters) or in the proposal stage (FP420 proton taggers and fast timing detectors).

Furthermore, a salient feature of the forward instrumentation around the interaction point (IP) of CMS is the presence of TOTEM [4]. TOTEM is an approved experiment at the LHC for measuring the $pp$ elastic cross section as a function of the four-momentum transfer squared, $t$, and for measuring the total cross section with a precision of approximately 1%. The TOTEM experiment uses the same IP as CMS and supplements around the CMS IP several tracking devices, located inside of the volume of the main CMS detector, plus near-beam proton taggers a distance up to ±220 m. The CMS and TOTEM collaborations have described the considerable physics potential of joint data taking in a report to the LHCC [1].

The kinematic coverage of the combined CMS and TOTEM apparatus is unprecedented at a hadron collider. It would be even further enhanced by complementing CMS with the detectors of the FP420 proposal which would induce forward physics into the portfolio of possible discovery processes at the LHC [2].

An overview of the forward instrumentation up to ±220 m from the CMS IP is given in Fig. 1. There are two suites of calorimeters with tracking detectors in front. The CMS Hadron Forward (HF) calorimeter with the TOTEM telescope T1 in front covers the region $3 < |\eta| < 5$, the CMS CASTOR calorimeter with the TOTEM telescope T2 in front covers $5.2 < |\eta| < 6.6$. The CMS ZDC calorimeters will be installed at the end of the straight LHC beam-line section, at a distance of ±140 m from the IP. Near-beam...
proton taggers will be installed by TOTEM at ±147 m and ±220 m from the IP. Further near-beam proton taggers in combination with very fast timing detectors to be installed at ±420 m from the IP are part of the FP420 proposal.

2. PHYSICS WITH FORWARD DETECTORS

In the following, we describe the physics interest of the CMS CASTOR and ZDC calorimeters [5] and the TOTEM T1 and T2 telescopes [2]. Of particular interest are QCD measurements at values of Bjorken-$x$ as low as $x \sim 10^{-6}$ and the resulting sensitivity to non-DGLAP dynamics, as well as forward particle and energy flow measurements. These can play an important role in tuning the Monte Carlo description of underlying event and multiple interactions at the LHC and in constraining Monte Carlo generators used for cosmic ray studies.

2.1. CMS CASTOR & ZDC calorimeters

The two calorimeters are of interest for $pp$, $pA$ and $AA$ running at the LHC, where $A$ denotes a heavy ion. They are Cherenkov-light devices with electromagnetic and hadronic sections and will be present in the first LHC $pp$ runs at luminosities where event pile-up should be low.

The CASTOR calorimeters are octagonal cylinders located at $\sim 14$ m from the IP. They are sampling calorimeters with tungsten plates as absorbers and fused silica quartz plates as active medium. The plates are inclined by 45° with respect to the beam axis. Particles passing through the quartz emit Cherenkov photons which are transmitted to photomultiplier tubes through aircore lightguides. The electromagnetic section is 22 radiation lengths $X_0$ deep with 2 tungsten-quartz sandwiches, the hadronic section consists of 12 tungsten-quartz sandwiches. The total depth is 10.3 interaction lengths $\lambda_l$. The calorimeters are read out segmented azimuthally in 16 segments and logitudinally in 14 segments. They do not have any segmentation in $\eta$. The CASTOR coverage of $5.2 < |\eta| < 6.6$ closes hermetically the total CMS calorimetric pseudorapidity range over 13 units.

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The ZDC calorimeters are already installed and will be operational already in 2008.

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The TOTEM T1 telescope consists of two arms symmetrically installed around the CMS IP in the endcaps of the CMS magnet, right in front of the
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The two arms of the TOTEM T2 telescope are mounted right in front of the CASTOR calorimeters, with similar \( \eta \) coverage. Each arm consists of 10 planes of 20 semi-circular modules of Gas Electron Multipliers (GEMs). The detector read-out is organized in strips and pads, a resolution of 115 \( \mu \text{m} \) for the radial coordinate and of 16 \( \mu \text{rad} \) in azimuthal angle were reached in prototype test beam measurements.

### 2.3. Proton-proton collisions at low \( x_{Bj} \)

In order to arrive at parton-parton interactions at very low \( x_{Bj} \) values, several steps in the QCD cascade initiated by the partons from the proton may occur before the final hard interaction takes place. Low-\( x_{Bj} \) QCD hence offers ideal conditions for studying the QCD parton evolution dynamics. Measurements at the HERA \( ep \) collider have explored low-\( x_{Bj} \) dynamics down to values of a few \( 10^{-5} \). At the LHC the minimum accessible \( x \) decreases by a factor \( \sim 10 \) for each 2 units of rapidity. A process with a hard scale of \( Q \) 10 GeV and within the acceptance of T2/CASTOR (\( \eta = 6 \)) can occur at \( x \) values as low as \( 10^{-6} \).

Forward particles at the LHC can be produced in collisions between two partons with \( x_1 \gg x_2 \), in which case the hard interaction system is boosted forward. An example is Drell-Yan production of \( e^+e^- \) pairs, \( qq \rightarrow \gamma^* \rightarrow e^+e^- \), a process that probes primarily the quark content of the proton. Figure 2 shows the distribution of the invariant mass \( M \) of the \( e^+e^- \) system versus the \( x_{Bj} \) of one of the quarks, where \( x_2 \) is chosen such that \( x_1 \gg x_2 \). The solid curve shows the kinematic limit \( M_{\text{max}} = \sqrt{x_2} \). The dotted lines indicate the acceptance window for both electrons to be detectable in T2/CASTOR. For invariant masses of the \( e^+e^- \) system of \( M > 10 \text{ GeV} \), \( x_{Bj} \) values down to \( 10^{-6} \) are accessible.

The rapid rise of the gluon density in the proton with decreasing values of \( x_{Bj} \) observed by HERA in deep inelastic scattering cannot continue indefinitely without violating unitarity at some point. Hence, parton recombination within the proton must set in at low enough values of \( x_{Bj} \) and leads to non-linear terms in the QCD gluon evolution. Figure 3 compares for Drell-Yan processes with both electrons within the T2/CASTOR detector acceptance the cross section predicted by a PDF model without (CTEQ5L [5]) and with (EHKQS [6]) saturation effects. A difference of a factor 2 is visible in the predictions. Further details can be found in [1].

Complementary information on the QCD evolution at low \( x_{Bj} \) can be gained from forward jets. The DGLAP evolution [7] assumes that parton emission in the cascade is strongly ordered in transverse momentum while in the BFKL evolution [8], no ordering in \( k_t \) is assumed, but strong
ordering in $x$. At small $x_{Bj}$, the difference between the two approaches is expected to be most pronounced for hard partons created at the beginning of the cascade, at pseudorapidities close to the proton, i.e. in the forward direction. Monte Carlo generator studies indicate that the resulting excess of forward jets with high $p_T$, observed at HERA, might be measurable with T2/CASTOR. Another observable sensitive to BFKL-like QCD evolution dynamics are dijets with large rapidity separation, which enhances the available phase space for BFKL-like parton radiation between the jets. Likewise dijets separated by a large rapidity gap are of interest since they indicate a process in which no color flow occurs in the hard scatter but where, contrary to the traditional picture of soft Pomeron exchange, also a high transverse momentum transfer occurs across the gap.

2.4. Multiplicity & energy flow

The forward detectors can be valuable tools for Monte Carlo tuning.

The hard scatter in hadron-hadron collisions takes place in a dynamic environment, referred to as the “underlying event” (UE), where additional soft or hard interactions between the partons and initial and final state radiation occur. The effect of the UE can not be disentangled on an event-by-event basis and needs to be included by means of tuning Monte Carlo multiplicities and energy flow predictions to data. The predictive power of these tunes obtained from Tevatron data is very limited, and ways need to be found to constrain the UE at LHC energies with LHC data. As shown in [9], the forward detectors are sensitive to features of the UE which central detector information alone cannot constrain.

Another area with high uncertainties is modelling the interaction of primary cosmic rays in the PeV energy range with the atmosphere. Their rate of occurrence per year is too low for reliable quantitative analysis. The center-of-mass energy in $pp$ collisions at the LHC corresponds to 100 PeV energy in a fixed target collision. Figure 4 shows the energy flow as function of pseudorapidity as predicted by different Monte Carlos in use in the cosmic ray community. Clear differences

Figure 3. Comparison of the cross section prediction of a model without (CTEQ5L) and with (EHKQS) saturation for Drell-Yan events in which both electrons are detected in T2/CASTOR.

Figure 4. Energy flow as predicted by Monte Carlo generators used for the description of cosmic ray induced air showers [1].
in the predictions are visible in the acceptance region of T2/CASTOR and ZDC.

3. PHYSICS WITH A VETO ON FORWARD DETECTORS

Events of the type $pp \to pXp$ or $pp \to Xp$, where no color exchange takes place between the proton(s) and the system $X$, can be caused by $\gamma$ exchange, or by diffractive interactions. In both cases, the absence of color flow between the proton(s) and the system $X$ results in a large gap in the rapidity distribution of the hadronic final state. Such a gap can be detected by requiring the absence of a signal in the forward detectors. In the following, we discuss three exemplary processes which are characterized by a large rapidity gap in their hadronic final state.

3.1. Diffraction with a hard scale

Diffraction, traditionally thought of as soft processes and described in Regge theory, can also occur with a hard scale ($W$, dijets, heavy flavors) as has been experimentally observed at UA8, HERA and Tevatron. In the presence of a hard scale, diffractive processes can be described in perturbative QCD (pQCD) and their cross sections can be factorized into that one of the hard scatter and a diffractive particle distribution function (dPDF). In diffractive hadron-hadron scattering, rescattering between spectator particles breaks the factorization. The so-called rapidity gap survival probability quantifies this effect [10]. A measure for it can be obtained by the ratio of diffractive to inclusive processes with the same hard scale. At the Tevatron, the ratio is found to be $\mathcal{O}(1\%)$ [11]. Theoretical expectations for the LHC vary from a fraction of a percent to as much as $30\%$ [12].

Single diffractive $W$ production, $pp \to pX$, where $X$ includes a $W$, is an example for diffraction with a hard scale at the LHC and is in particular sensitive to the quark component of the proton dPDF in an as-of-yet unmeasured region. In the absence of event pile-up, a selection is possible based on the requirement that there be no activity above noise level in the CMS forward calorimeters HF and CASTOR.

Figure 5 shows the number of towers with activity above noise level in HF versus in CASTOR. The decay channel is $W \to \mu\nu$ and a rapidity gap survival factor of $5\%$ is assumed in the diffractive Monte Carlo sample (Pomwig). The number of events is normalized to an integrated luminosity of $100$ pb$^{-1}$ [13].

The study assumes that CASTOR will be available only on one side. A second CASTOR in the opposite hemisphere and the use of T1, T2 will improve the observable excess further.

3.2. Exclusive dilepton production

Exclusive dimuon and dielectron production with no significant additional activity in the CMS detector occurs with high cross section in gamma-mediated processes at the LHC, either as the pure QED process $\gamma\gamma \to l\ell$ or in $T$ photoproduction. Photoproduction of $J/\psi$ mesons is also possible, but difficult to observe because of the trigger thresholds for
A feasibility study to detect them with CMS was presented in this workshop [14].

The event selection is based on requiring that outside of the two leptons, no other significant activity is visible within the central CMS detector, neither in the calorimeter nor in the tracking system. In $100 \text{ pb}^{-1}$ of single interaction data, $\mathcal{O}(700)$ events in the dimuon channels and $\mathcal{O}(70)$ in the dielectron channel can be selected. Events in which one of the protons in the process does not stay intact but dissociates are the dominant source of background and are comparable in statistics to the signal. This background can be significantly reduced by means of a veto condition on activity in CASTOR and ZDC, in a configuration with a ZDC on each side and a CASTOR on only one side of the IP by $2/3$.

The theoretically very precisely known cross section of the almost pure QED process $pp \rightarrow \pi l\pi p$ via $\gamma$ exchange is an ideal calibration channel. With $100 \text{ pb}^{-1}$ of data, an absolute luminosity calibration with 4% precision is feasible. Furthermore, exclusive dimuon production is an ideal alignment channel with high statistics for the proposed proton taggers at 420 m from the IP. Upsilon photoproduction can constrain QCD models of diffraction, as discussed in the next section.

The $\gamma\gamma \rightarrow e^+e^-$ process has recently been observed at the Tevatron [16].

3.3. Upsilon photoproduction

Assuming the STARLIGHT [17] Monte Carlo cross section prediction, the 1S, 2S and 3S resonances will be clearly visible in $100 \text{ pb}^{-1}$ of single interaction data. With their average $\gamma p$ center-of-mass energy of $< W_{\gamma p} \gtrsim 2400 \text{ GeV}^2$, they will extend the accessible range of the HERA measurement of the $W_{\gamma p}$ dependence of $\sigma(\gamma p \rightarrow \Upsilon(1S)p)$ by one order of magnitude.

By means of the $p_T^2$ value of the $\Upsilon$ as estimator of the transferred four-momentum squared, $t$, at the proton vertex, it might be possible to measure the $t$ dependence of the cross section. This dependence is sensitive to the two-dimensional gluon distribution of the proton and would give access to the generalized parton distribution function (GPD) of the proton.

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Figure 6. Invariant mass of exclusive dimuon production in the Upsilon mass region [15]

4. PHYSICS WITH NEAR-BEAM PROTON TAGGERS

For slightly off-momentum protons, the LHC beamline with its magnets is essentially a spectrometer. If a scattered proton is bent sufficiently, but little enough to remain within the beam-pipe, they can be detected by means of detectors inserted into the beam-pipe and approaching the beam envelope as closely as possible. At high luminosity at the LHC, large rapidity gaps typical for diffractive events or events with $\gamma$ exchange tend to be filled in by particles from overlaid pile-up events. Hence tagging the outgoing scattered proton(s) becomes the only mean of detection at high luminosities.

4.1. TOTEM and FP420 proton taggers

The TOTEM proton taggers, located at $\pm 147$ m and $\pm 220$ m from the IP, each consist of Silicon strip detectors housed in movable Roman Pots [4]. The detector design is such that the beam can be approached up to a minimal distance of $10\sigma + 0.5$ mm. With nominal LHC beam optics, scattered protons from the IP are within the acceptance of the taggers at 220 m when for their fractional momentum loss $\xi$ holds:

$0.02 < \xi < 0.2$.

In order to achieve acceptance at smaller values of $\xi$ with nominal LHC beam optics, detectors...
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4.2. Physics potential

Forward proton tagging capabilities enhance the physics potential of CMS. They would render possible a precise measurement of the mass and quantum numbers of the Higgs boson should it be discovered by traditional searches. They also augment the CMS discovery reach for Higgs production in the minimal supersymmetric extension (MSSM) of the Standard Model (SM) and for physics beyond the SM in $\gamma p$ and $\gamma \gamma$ interactions.

A case in point is the central exclusive production (CEP) process \cite{19}, $pp \rightarrow p + \phi + p$, where the plus sign denotes the absence of hadronic activity between the outgoing protons, which survive the interaction intact, and the state $\phi$. The final state consists solely of the scattered protons, which may be detected in the forward proton taggers, and the decay products of $\phi$ which can be detected in the central CMS detector. Selection rules force the produced state $\phi$ to have $J^{CP} = n^{++}$ with $n = 0, 2, \ldots$. This process offers hence an experimentally very clean laboratory for the discovery of any particle with these quantum numbers that couples strongly to gluons. Additional advantages are the possibility to determine the mass of the state $\phi$ with excellent resolution from the scattered protons alone, independent of its decay products, and the possibility, unique at the LHC, to determine the quantum numbers of $\phi$ directly from the azimuthal asymmetry between the scattered protons.

In the case of a SM Higgs boson with mass close to the current exclusion limit, which decays preferably into $b\bar{b}$, CEP improves the achievable...
signal-to-background ratio dramatically, to $O(1)$ \cite{2,20}. In certain regions of the MSSM, generally known as “LHC wedge region”, the heavy MSSM Higgs bosons would escape detection at the LHC. There, the preferred search channels at the LHC are not available because the heavy Higgs bosons decouple from gauge bosons while their couplings to $b\bar{b}$ and $\tau\bar{\tau}$ are enhanced at high $\tan\beta$. Figure 8 depicts the 5 $\sigma$ discovery contour for the $H \rightarrow b\bar{b}$ channel in CEP in the $M_A - \tan\beta$ plane of the MSSM within the $M_A^{max}$ benchmark scenario with $\mu = +200$ GeV and for different integrated luminosities. The values of the mass of the heavier CP-even Higgs boson, $M_H$, are indicated by contour lines. The dark region corresponds to the parameter region excluded by LEP.

Forward proton tagging will also give access to a rich QCD program on hard diffraction at high luminosities, where event pile-up is significant and makes undetectable the gaps in the hadronic final state otherwise typical of diffraction. Detailed studies with high statistical precision will be possible on skewed, unintegrated gluon densities; Generalized Parton Distributions which contain information on the correlations between partons in the proton; and the rapidity gap survival probability, a quantity closely linked to soft rescattering effects and the features of the underlying event at the LHC.

Forward proton tagging also provides the possibility for precision studies of $\gamma\gamma$ and $\gamma p$ interactions at center-of-mass energies never reached before. Anomalous top production, anomalous gauge boson couplings, exclusive dilepton production and quarkonia production are possible topics, as was discussed in detail at this workshop.

5. SUMMARY

Forward physics in $pp$ collisions at the LHC covers a wide range of diverse physics subjects (low-$x_{Bj}$ QCD, hard diffraction, $\gamma\gamma$ and $\gamma p$ interactions) which have in common that particles produced at large values of rapidity provide a defining characteristics. For the CMS detector, several subdetectors with forward $\eta$ coverage are currently under construction (CASTOR, ZDC) or in the proposal stage (FP420). The TOTEM experiment supplements around the CMS IP several tracking devices and near-beam proton taggers at distances up to $\pm 220$ m. The kinematic coverage of the combined CMS and TOTEM apparatus is unprecedented at a hadron collider. It would be even further enhanced by complementing CMS with the detectors of the FP420 proposal which would add forward physics to the portfolio of possible discovery processes at the LHC.

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2.3. Proton-proton collisions at low $x_{Bj}$

In order to arrive at parton-parton interactions at very low $x_{Bj}$ values, several steps in the QCD cascade initiated by the partons from the proton may occur before the final hard interaction takes place. Low-$x_{Bj}$ QCD hence offers ideal conditions for studying the QCD parton evolution dynamics. Measurements at the HERA $ep$ collider have explored low-$x_{Bj}$ dynamics down to values of a few $10^{-5}$. At the LHC the minimum accessible $x$ decreases by a factor $\sim 10$ for each 2 units of rapidity. A process with a hard scale of $Q \, 10 \, \text{GeV}$ and within the acceptance of T2/CASTOR ($\eta = 6$) can occur at $x$ values as low as $10^{-6}$.

Forward particles at the LHC can be produced in collisions between two partons with $x_1 >> x_2$, in which case the hard interaction system is boosted forward. An example is Drell-Yan production of $e^+e^-$ pairs, $q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$, a process that probes primarily the quark content of the proton. Figure 2 shows the distribution of the invariant mass $M$ of the $e^+e^-$ system versus the $x_{Bj}$ of one of the quarks, where $x_2$ is chosen such that $x_1 >> x_2$. The solid curve shows the kinematic limit $M_{\text{max}} = \sqrt{x_2 s}$. The dotted lines indicate the acceptance window for both electrons to be detectable in T2/CASTOR. For invariant masses of the $e^+e^-$ system of $M > 10 \, \text{GeV}$, $x_{Bj}$ values down to $10^{-6}$ are accessible.

The rapid rise of the gluon density in the proton with decreasing values of $x_{Bj}$ observed by HERA in deep inelastic scattering cannot continue indefinitely without violating unitarity at some point. Hence, parton recombination within the proton must set in at low enough values of $x_{Bj}$ and leads to non-linear terms in the QCD gluon evolution. Figure 3 compares for Drell-Yan processes with both electrons within the T2/CASTOR detector acceptance the cross section predicted by a PDF model without (CTEQ5L [5]) and with (EHKQS [6]) saturation effects. A difference of a factor 2 is visible in the predictions. Further details can be found in [1].

Complementary information on the QCD evolution at low $x_{Bj}$ can be gained from forward jets. The DGLAP evolution [7] assumes that parton emission in the cascade is strongly ordered in transverse momentum while in the BFKL evolution [8], no ordering in $k_t$ is assumed, but strong
ordering in $x$. At small $x_{Bj}$, the difference between the two approaches is expected to be most pronounced for hard partons created at the beginning of the cascade, at pseudorapidities close to the proton, i.e. in the forward direction. Monte Carlo generator studies indicate that the resulting excess of forward jets with high $p_T$, observed at HERA, might be measurable with T2/CASTOR. Another observable sensitive to BFKL-like QCD evolution dynamics are dijets with large rapidity separation, which enhances the available phase space for BFKL-like parton radiation between the jets. Likewise dijets separated by a large rapidity gap are of interest since they indicate a process in which no color flow occurs in the hard scatter but where, contrary to the traditional picture of soft Pomeron exchange, also a high transverse momentum transfer occurs across the gap.

2.4. Multiplicity & energy flow

The forward detectors can be valuable tools for Monte Carlo tuning.

The hard scatter in hadron-hadron collisions takes place in a dynamic environment, referred to as the “underlying event” (UE), where additional soft or hard interactions between the partons and initial and final state radiation occur. The effect of the UE can not be disentangled on an event-by-event basis and needs to be included by means of tuning Monte Carlo multiplicities and energy flow predictions to data. The predictive power of these tunes obtained from Tevatron data is very limited, and ways need to be found to constrain the UE at LHC energies with LHC data. As shown in [9], the forward detectors are sensitive to features of the UE which central detector information alone cannot constrain.

Another area with high uncertainties is modelling the interaction of primary cosmic rays in the PeV energy range with the atmosphere. Their rate of occurrence per year is too low for reliable quantitative analysis. The center-of-mass energy in $pp$ collisions at the LHC corresponds to 100 PeV energy in a fixed target collision. Figure 4 shows the energy flow as function of pseudorapidity as predicted by different Monte Carlos in use in the cosmic ray community. Clear differences

Figure 3. Comparison of the cross section prediction of a model without (CTEQ5L) and with (EHKQS) saturation for Drell-Yan events in which both electrons are detected in T2/CASTOR.
in the predictions are visible in the acceptance region of T2/CASTOR and ZDC.

3. PHYSICS WITH A VETO ON FORWARD DETECTORS

Events of the type \( pp \to pXp \) or \( pp \to Xp \), where no color exchange takes place between the proton(s) and the system \( X \), can be caused by \( \gamma \) exchange, or by diffractive interactions. In both cases, the absence of color flow between the proton(s) and the system \( X \) results in a large gap in the rapidity distribution of the hadronic final state. Such a gap can be detected by requiring the absence of a signal in the forward detectors. In the following, we discuss three exemplary processes which are characterized by a large rapidity gap in their hadronic final state.

3.1. Diffraction with a hard scale

Diffraction, traditionally thought of as soft process and described in Regge theory, can also occur with a hard scale (\( W \), dijets, heavy flavors) as has been experimentally observed at UA8, HERA and Tevatron. In the presence of a hard scale, diffractive processes can be described in perturbative QCD (pQCD) and their cross sections can be factorized into that one of the hard scatter and a diffractive particle distribution function (dPDF). In diffractive hadron–hadron scattering, rescattering between spectator particles breaks the factorization. The so-called rapidity gap survival probability quantifies this effect [10]. A measure for it can be obtained by the ratio of diffractive to inclusive processes with the same hard scale. At the Tevatron, the ratio is found to be \( \mathcal{O}(1\%) \) [11]. Theoretical expectations for the LHC vary from a fraction of a percent to as much as 30% [12].

Single diffractive \( W \) production, \( pp \to pX \), where \( X \) includes a \( W \), is an example for diffraction with a hard scale at the LHC and is in particular sensitive to the quark component of the proton dPDF in an as-of-yet unmeasured region. In the absence of event pile-up, a selection is possible based on the requirement that there be no activity above noise level in the CMS forward calorimeters HF and CASTOR.

Figure 5 shows the number of towers with activity above noise level in HF versus in CASTOR. The decay channel is \( W \to \mu\nu \) and a rapidity gap survival factor of 5% is assumed in the diffractive Monte Carlo sample (Pomwig). The number of events is normalized to an integrated luminosity of 100 pb\(^{-1}\) of single interactions (i.e., no event pile-up). In the combined Pomwig + Pythia Monte Carlo sample, a clear excess in the bin \([n(\text{Castor}), n(\text{HF})] = [0,0]\) is visible, of \( \mathcal{O}(100) \) events. The ratio of diffraction to non-diffraction in the \([0,0]\) bin of approximately 20 demonstrate the feasibility of observing single diffractive \( W \) production at the LHC.

The study assumes that CASTOR will be available only on one side. A second CASTOR in the opposite hemisphere and the use of T1, T2 will improve the observable excess further.

3.2. Exclusive dilepton production

Exclusive dimuon and dielectron production with no significant additional activity in the CMS detector occurs with high cross section in gamma-mediated processes at the LHC, either as the pure QED process \( \gamma\gamma \to ll \) or in \( T \) photoproduction.\(^2\) Photoproduction of \( J/\psi \) mesons is also possible, but difficult to observe because of the trigger thresholds for

\(^2\)Photoproduction of \( J/\psi \) mesons is also possible, but difficult to observe because of the trigger thresholds for
A feasibility study to detect them with CMS was presented in this workshop [14].

The event selection is based on requiring that outside of the two leptons, no other significant activity is visible within the central CMS detector, neither in the calorimeter nor in the tracking system. In 100 pb$^{-1}$ of single interaction data, $\mathcal{O}(700)$ events in the dimuon channels and $\mathcal{O}(70)$ in the dielectron channel can be selected. Events in which one of the protons in the process does not stay intact but dissociates are the dominant source of background and are comparable in statistics to the signal. This background can be significantly reduced by means of a veto condition on activity in CASTOR and ZDC, in a configuration with a ZDC on each side and a CASTOR on only one side of the IP by 2/3.

The theoretically very precisely known cross section of the almost pure QED process $pp \rightarrow pllp$ via $\gamma$ exchange is an ideal calibration channel. With 100pb$^{-1}$ of data, an absolute luminosity calibration with 4% precision is feasible. Furthermore, exclusive dimuon production is an ideal alignment channel with high statistics for the proposed proton taggers at 420 m from the IP. Upsilon photoproduction can constrain QCD models of diffraction, as discussed in the next section. The $\gamma\gamma \rightarrow e^+e^-$ process has recently been observed at the Tevatron [16].

3.3. Upsilon photoproduction

Assuming the STARLIGHT [17] Monte Carlo cross section prediction, the 1S, 2S and 3S resonances will be clearly visible in 100pb$^{-1}$ of single interaction data. With their average $\gamma p$ center-of-mass energy of $< W_{\gamma p} > \approx 2400$GeV$^2$, they will extend the accessible range of the HERA measurement of the $W_{\gamma p}$ dependence of $\sigma(\gamma p \rightarrow \Upsilon(1S)p)$ by one order of magnitude.

By means of the $p_T^2$ value of the $\Upsilon$ as estimator of the transferred four-momentum squared, $t$, at the proton vertex, it might be possible to measure the $t$ dependence of the cross section. This dependence is sensitive to the two-dimensional gluon distribution of the proton and would give access to the generalized parton distribution function (GPD) of the proton.

4. PHYSICS WITH NEAR-BEAM PROTON TAGGERS

For slightly off-momentum protons, the LHC beamline with its magnets is essentially a spectrometer. If a scattered proton is bent sufficiently, but little enough to remain within the beam-pipe, they can be detected by means of detectors inserted into the beam-pipe and approaching the beam envelope as closely as possible. At high luminosity at the LHC, large rapidity gaps typical for diffractive events or events with $\gamma$ exchange tend to be filled in by particles from overlaid pile-up events. Hence tagging the outgoing scattered proton(s) becomes the only mean of detection at high luminosities.

4.1. TOTEM and FP420 proton taggers

The TOTEM proton taggers, located at $\pm 147$ m and $\pm 220$ m from the IP, each consist of Silicon strip detectors housed in movable Roman Pots [3]. The detector design is such that the beam can be approached up to a minimal distance of 10$\sigma + 0.5$ mm. With nominal LHC beam optics, scattered protons from the IP are within the acceptance of the taggers at 220 m when for their fractional momentum loss $\xi$ holds: 0.02 $< \xi < 0.2$.

In order to achieve acceptance at smaller values of $\xi$ with nominal LHC beam optics, detectors...
Forward detectors around the CMS interaction point at LHC and their physics potential

Figure 7. Acceptance in $x_L = 1 - \xi$, where $\xi$ is the fractional momentum loss of the scattered proton, of the TOTEM and FP420 proton taggers. The data points shown are from ZEUS [18].

have to be located further away from the IP. Proton taggers at $\pm 420$ m from the IP have an acceptance of $0.002 < \xi < 0.02$, complementing taggers at 220 m, as shown in Figure 7. The proposal [2] of the FP420 R&D collaboration foresees employing 3-D Silicon, an extremely radiation hard novel Silicon technology, for the proton taggers. Additional fast timing Cherenkov detectors will be capable of determining, within a resolution of a few millimeters, whether the tagged proton came from the same vertex as the hard scatter visible in the central CMS detector. In order to comply with the space constraints of the location within the cryogenic region of the LHC, these detectors will be attached to a movable beam-pipe with the help of which the detectors can approach the beam to within 3 mm.

The FP420 proposal is currently under scrutiny in CMS and ATLAS. If approved, installation could proceed in 2010, after the LHC start-up.

4.2. Physics potential

Forward proton tagging capabilities enhance the physics potential of CMS. They would render possible a precise measurement of the mass and quantum numbers of the Higgs boson should it be discovered by traditional searches. They also augment the CMS discovery reach for Higgs production in the minimal supersymmetric extension (MSSM) of the Standard Model (SM) and for physics beyond the SM in $\gamma p$ and $\gamma \gamma$ interactions.

A case in point is the central exclusive production (CEP) process [19], $pp \rightarrow p + \phi + p$, where the plus sign denotes the absence of hadronic activity between the outgoing protons, which survive the interaction intact, and the state $\phi$. The final state consists solely of the scattered protons, which may be detected in the forward proton taggers, and the decay products of $\phi$ which can be detected in the central CMS detector. Selection rules force the produced state $\phi$ to have $J^{CP} = n^+^+$ with $n = 0, 2, ...$. This process offers hence an experimentally very clean laboratory for the discovery of any particle with these quantum numbers that couples strongly to gluons. Additional advantages are the possibility to determine the mass of the state $\phi$ with excellent resolution from the scattered protons alone, independent of its decay products, and the possibility, unique at the LHC, to determine the quantum numbers of $\phi$ directly from the azimuthal asymmetry between the scattered protons.

In the case of a SM Higgs boson with mass close to the current exclusion limit, which decays preferentially into $b\bar{b}$, CEP improves the achievable signal-to-background ratio dramatically, to $O(1)$ [21].

Figure 8. Five $\sigma$ discovery contours for central exclusive production of the heavier CP-even Higgs boson $H$ [21]. See text for details.
In certain regions of the MSSM, generally known as “LHC wedge region”, the heavy MSSM Higgs bosons would escape detection at the LHC. There, the preferred search channels at the LHC are not available because the heavy Higgs bosons decouple from gauge bosons while their couplings to $b\bar{b}$ and $\tau\bar{\tau}$ are enhanced at high $\tan\beta$. Figure 8 depicts the $5\sigma$ discovery contour for the $H \rightarrow b\bar{b}$ channel in CEP in the $M_A - \tan\beta$ plane of the MSSM within the $M_h^{\text{max}}$ benchmark scenario with $\mu = +200$ GeV and for different integrated luminosities. The values of the mass of the heavier CP-even Higgs boson, $M_H$, are indicated by contour lines. The dark region corresponds to the parameter region excluded by LEP.

Forward proton tagging will also give access to a rich QCD program on hard diffraction at high luminosities, where event pile-up is significant and makes undetectable the gaps in the hadronic final state otherwise typical of diffraction. Detailed studies with high statistical precision will be possible on skewed, unintegrated gluon densities; Generalized Parton Distributions which contain information on the correlations between partons in the proton; and the rapidity gap survival probability, a quantity closely linked to soft rescattering effects and the features of the underlying event at the LHC.

Forward proton tagging also provides the possibility for precision studies of $\gamma p$ and $\gamma\gamma$ interactions at center-of-mass energies never reached before. Anomalous top production, anomalous gauge boson couplings, exclusive dilepton production and quarkonia production are possible topics, as was discussed in detail at this workshop.

5. SUMMARY

Forward physics in $pp$ collisions at the LHC covers a wide range of diverse physics subjects (low-$x_{Bj}$ QCD, hard diffraction, $\gamma\gamma$ and $\gamma p$ interactions) which have in common that particles produced at large values of rapidity provide a defining characteristics. For the CMS detector, several subdetectors with forward $\eta$ coverage are currently under construction (CASTOR, ZDC) or in the proposal stage (FP420). The TOTEM experiment supplements around the CMS IP several tracking devices and near-beam proton taggers at distances up to $\pm 220$ m. The kinematic coverage of the combined CMS and TOTEM apparatus is unprecedented at a hadron collider. It would be even further enhanced by complementing CMS with the detectors of the FP420 proposal which would add forward physics to the portfolio of possible discovery processes at the LHC.

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